Improving Greenhouse Gas Emission Calculations from Forest Fires in Sweden

Evaluating and Refining Biomass Assumptions, Burned Area Accuracy, and Emission Methodologies Using Swedish National Data

Markus Riemer

Degree project • 30 credits
Swedish University of Agricultural Sciences, SLU
Department of Soil and Environement
Environmental Science (EnvEuro) – Soil, Water and Biodiversity
Examensarbeten / Institutionen för mark & miljö, SLU
Number in series: 2025:17
Uppsala 2025

Improving Greenhouse Gas Emission Calculations from Forest Fires in Sweden. Evaluating and Refining Biomass Assumptions, Burned Area Accuracy, and Emission Methodologies Using Swedish National Data.

Förbättring av växthusgasberäkningar från skogsbränder i Sverige
Granskning och vidareutveckling av biomassantaganden, precision i brandavgränsning och utsläppsmetodik med stöd av svenska nationella datakällor

Markus Riemer

Supervisor:	**Mattias Lundblad, SLU Uppsala, Department of Soil and Environment**
Co-supervisor:	Harald Rieder, BOKU University, Institute of Meteorology and Climatology
Assistant supervisor:	Hans Petersson, SLU Umeå, Institute for Forest Resource Management
Advisor:	Inka Bohlin, SLU Umeå, Institute for Forest Resource Management
Examiner:	Nadia Maaroufi, SLU Uppsala, Department of Soil and Environment

Credits:	30 credits
Level:	Master's level (A2E)
Course title:	Master's Thesis in Environmental Science
Course code:	EX0897
Program/education:	Environmental Science (EnvEuro) – Soil, Water and Biodiversity
Course coordinating dept:	Department of Soil and Environment
Place of publication:	Uppsala
Year of publication:	2025

Keywords:	carbon emissions, greenhouse gas, emission inventory, estimation method, forest fire, wildfire

Swedish University of Agricultural Sciences
Faculty of Natural Resources and Agricultural Sciences
Department of Soil and Environment

Acknowledgements

First and foremost, I want to express my deepest admiration towards the person that was most affected by my stay in Sweden - my daughter Joy-Johanna. I cannot imagine how hard it was for her to not have her dad around for almost a year and how strong she needed to be to not show me how much she missed me every time we talked. You are an extraordinary person and I'm thankful to deserve your love. This cannot be said without also thanking her mother, Sabrina. Thank you for lending your ear and shoulder to Joy when I could not. Right after I want to express my deepest gratitude for my grandfather, Hermann Stieger: Your support - financially and emotionally – has been nothing short of generous. I never missed anything in my life as a student because of you – a privilege that stands very much in contrast to how you grew up. I'd be a lot less without you.

I want to deeply thank my main supervisor, Mattias Lundblad, for his kind and steady support from the beginning to the end of this work. I have the feeling that I got to know you better than any other Swede, and I appreciate your expertise and as much as your warm personality. To my co-supervisors, Harald Rieder (BOKU) and Hans Petersson (SLU Umeå): thank you for your thoughtful and technical feedback that helped me make the thesis better than I could on my own. I also want to extend my heartfelt thanks to Inka Bohlin, advisor from SLU Umeå. You did more for me than your role required, and I'm very thankful for the time and support you gave me along the way. My examiner, Nadia Maaroufi, gave me valuable and kind feedback early in the process, helping me to better frame and structure my work from the start. Thank you for your patience with me.

A very special thanks goes to Merlin Mayer. You did not spare me with critique and honest feedback which improved this work significantly. Luca Rahm, although already finished with her thesis, took the time to read mine and gave thoughtful comments instead of enjoying her well-earned break. Tack så mycket!

Additionally, I want to thank:

- Johan Sjöström, for sharing his expertise in setting up field visits;
- Christofer Engberg Hydén, for helping me getting started with R;
- Frida Carlstedt (Skogsstyrelsen), for her quick and clear answers that helped me understand the Swedish process of delineating fire polygons;
- Joakim Ekberg (MSB), for giving me insight into how wildfires are reported and where uncertainties could lie within the system.

Abstract

In this thesis, Sweden's current approach to estimating greenhouse gas emissions from forest fires was evaluated, and possible improvements were tested through a combination of spatial analysis, field observations, and methodological review. The national inventory currently applies a methodology broadly aligned with what the Intergovernmental Panel on Climate Change (IPCC) defines as Tier 1, assuming fixed values for biomass and combustion fractions. This study examined the validity of these assumptions by integrating national forest inventory data with site-specific biomass estimates derived from remote sensing. Alternative emission estimates were generated using updated national biomass values, county-level area-weighted biomass means, and fire-specific remote sensing data. In addition, the potential applicability of available datasets for future reporting was assessed through cross-validation with independent sources and literature. Field observations at selected fire sites suggested that the standard 25% combustion fraction likely overestimates the proportion of biomass actually burned. Emission estimates based on refined biomass data yielded significantly higher greenhouse gas values compared to the current default approach. The study concludes with recommendations for short-, medium-, and long-term methodological improvements to enhance the accuracy of Sweden's greenhouse gas inventory for forest fire emissions.

Keywords: carbon emissions, greenhouse gas, emission inventory, estimation method, forest fire, wildfire

Sammanfattning

I detta examensarbete har Sveriges nuvarande metod för att beräkna växthusgasutsläpp från skogsbränder utvärderats och möjliga förbättringar testats genom en kombination av rumslig analys, fältobservationer och metodgranskning. Den nationella växthusgasinventeringen tillämpar för närvarande en metod som i stort motsvarar vad FN:s klimatpanel (IPCC) definierar som Tier 1, där fasta värden för biomassa och förbränningsandelar antas. Denna studie undersöker giltigheten i dessa antaganden genom att integrera data från Riksskogstaxeringen med platsspecifika biomassaskattningar baserade på fjärranalys. Alternativa utsläppsberäkningar togs fram med uppdaterade nationella biomassavärden, länsvisa areavägda medelvärden och brandspecifika data från fjärranalys. Dessutom bedömdes tillgången och användbarheten hos befintliga datakällor för framtida rapportering genom korsvalidering med andra dataset och litteratur. Fältobservationer vid utvalda brandplatser antyder att den standardiserade förbränningsandelen på 25 procent sannolikt överskattar den faktiska andelen förbränd biomassa. Beräkningar med mer detaljerad biomassadata resulterade i avsevärt högre utsläppsvärden jämfört med den nuvarande standardmetoden. Studien avslutas med rekommendationer för kortsiktiga, medellånga och långsiktiga metodförbättringar för att öka noggrannheten i Sveriges rapportering av växthusgasutsläpp från skogsbränder.

Keywords: carbon emissions, greenhouse gas, emission inventory, estimation method, forest fire, wildfire

Table of contents

List of tables

List of figures

Abbreviations

Abbreviation	Description
ALS	Airborne Laser Scanning
CO_2-eq.	Carbon Dioxide Equivalent
DM	Dry Matter
DOM	Dead Organic Matter
FAO	Food and Agriculture Organization of the United Nations
FSC	Forest Stewardship Council
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPCC	International Panel on Climate Change
LULUCF	Land Use, Land-Use Change, and Forestry
MSB	Swedish Contingency Agency (Myndigheten för samhällsskydd och beredskap)
NFI	National Forest Inventory (Riksskogstaxeringen)
NILS	National Inventory of Landscapes in Sweden (Nationell Inventering av Landskapet i Sverige)
NIR	National Inventory Report
NMD	National Land Cover Database Sweden (Nationella marktäckesdatabasen)
SEPA	Swedish Environmental Protection Agency (Naturvårdsverket)
SFSI	Swedish Forest Soil Inventory
SKS	Swedish Forest Agency (Skogssyrelsen)
SLU	Swedish University of Agricultural Sciences (Sveriges lantbruksuniversitet)
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
RMSE	Root Mean Square Error
UNFCCC	United Nations Framework Convention on Climate Change

1. Introduction

1.1 Importance of estimating Greenhouse Gas emissions from forest fires

Forest ecosystems significantly influence the global carbon cycle by acting primarily as carbon sinks due to their ability to sequester atmospheric carbon dioxide (CO_2) into biomass and soils (IPCC 2019). Changes in these ecosystems can affect carbon stocks, which in turn impact net emissions in the Land Use, Land-Use Change, and Forestry (LULUCF) sector, monitored and reported by countries under the UNFCCC . Forests are exposed to several disturbances, such as harvests, storms, droughts, and fires, which can affect their carbon stocks, releasing carbon that is stored there back into the atmosphere. This is influencing global warming, especially if the emissions originate from fossil stocks (ibid.).

Forest fires produce emissions of several greenhouse gases (GHG), primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), alongside other gases such as carbon monoxide (CO) and nitrogen oxides (NO_x) (IPCC 2006). Methane, constituting roughly one-tenth of emitted organic hydrocarbons, is particularly significant due to its strong greenhouse effect (Sjöström et al. 2024)

The Intergovernmental Panel on Climate Change (IPCC) provides methodological guidelines to estimate emissions from forest fires, recommending a general assumption that around 50% of the combusted biomass is carbon, which forms the basis for calculating both CO_2 and non-CO_2 emissions (IPCC 2006). However, not all biomass burns completely: it can either be left to decomposed over the course of decades or remain as charcoal, which, instead of a release, constitute a long-term depot of carbon in forest soils (ibid.).

In managed forests, regrowing vegetation can offset carbon losses through subsequent carbon uptake. This sequestration process, however, is not immediate. Forests may need decades or even centuries, depending on forest type, climatic conditions, and fire severity, to recapture the equivalent amount of carbon released during a single fire event (IPCC 2019).

Accurate estimation and monitoring of greenhouse gas emissions from forest fires is therefore essential for reliable national and international climate reporting which can serve as basis for effective climate mitigation strategies. Robust emission inventories can also inform adaptive forest management practices and support evidence-based policy decisions that help minimizing the future climate impact of forest disturbances.

1.2 Role of forest fires in boreal forests

In boreal ecosystems, fire regimes vary in severity, encompassing a spectrum from low-intensity surface fires to rare, stand-replacing crown fires. While crown fires dominate large regions of boreal North America, such events are exceptionally rare in Fennoscandia and rarely cover large areas. Instead, surface fires have historically prevailed in the boreal forests of Sweden and Finland, reflecting a natural dominance of lower-intensity regimes (Shorohova et al. 2011). This distinction was recently attributed to differences in tree species distribution, namely to the widespread occurrence of the highly flammable black spruce in North America's forests (Rogers et al. 2015).

Boreal forests, when faced with extreme drought conditions are at particular risk of emitting significant amounts of GHG emissions. Fires occurring after prolonged dry periods can consume extensive organic layers, which can strongly amplify carbon emissions. The regeneration of humus layers after such intense fires is a notably slow process, taking place over centuries rather than decades (Sjöström et al. 2024). Additionally, fires following severe drought conditions in the Nordic region can penetrate deeply into peatlands, particularly if drained, thereby releasing substantial quantities of fossil carbon into the atmosphere. For each centimetre of peat burnt per hectare, between 9 and 18 tonnes of fossil CO_2 can be emitted (ibid.), representing a permanent addition to atmospheric carbon pools.

1.3 Significance of forest fires in Sweden

Historically, wildfires in Sweden occurred frequently, with intervals of 80–100 years in the north and even more often in the south. However, over the last 150 years, large-scale forestry and increasingly effective fire suppression have reduced the proportion of burnt forest almost completely (Shorohova et al. 2011; Sjöström et al. 2024), leading to a loss of fire-affected habitats thereby negatively impacting pyrophilic species and forest biodiversity (Sjöström & Granström 2020).

In modern times, Sweden experiences relatively low levels of wildfire activity compared to other boreal regions (Rogers et al. 2015). Between 2000 and 2023, only two years (2014 and 2018) saw major wildfire events. For the remaining years, wildfires contributed less than 0.2 Mt CO_2-eq. annually based on the current reporting methodology, which is a minor share of total national emissions (Naturvårdsverket 2025). In an average year, wildfires affect approximately 0.01% of Sweden's forest area, while in the extreme fire year of 2018, about 0.09% of the total forested land (28 million ha) was burned (ibid.).

Alongside wildfires, Sweden's forests also experience prescribed or controlled burnings, primarily for ecological conservation and forest regeneration purposes. Conservation burnings are implemented in nature reserves and protected forests to support fire-adapted species and promote biodiversity (Naturvårdsverket & Skogsstyrelsen 2023; Sjöström et al. 2024). Their use has increased steadily since the 1990s, particularly following the establishment of FSC[1] certification standards and initiatives such as the LIFE Taiga project[2], which enhanced national expertise and capacity for planned burnings . These burnings are typically conducted in spring under moist conditions, resulting in rather limited impact on carbon stocks (Sjöström et al. 2024). Regeneration burnings, however, which are often implemented by forest companies on clear-cut areas with significant fuel loads, can result in high fire intensity and tree mortality (Granström 2001).

Because of the limited annual area burned in Sweden today, emission calculations from forest fires had received comparably little attention in the past years. However, an projected increase in fire danger levels and length of fire season

[1] Forest Stewardship Council – see https://fsc.org/en

[2] https://lifetaiga.se/controlled-burning-in-woodlands/

(San-Miguel-Ayanz et al. 2023) as well as the increase in controlled burnings over the last decades (Ramberg et al. 2018) stresses the need for more accurate GHG emission estimates. The actual amount of carbon combusted during wildfires remains mostly uncertain due to incomplete data on fuel stocks and a high variability in fire intensity . To better understand the potential climate impact of forest fires and improve the accuracy of national reporting, it is essential to first examine which pools of a forest system store carbon and how these might be affected during fire events.

1.4 Forest carbon pools

Forests store carbon across multiple interconnected pools. All of these pools contribute to the dynamics of GHG emissions and can be altered in one or the other way through forest fires (IPCC 2006). However, their susceptibility to combustion differes and their specific role in emission reporting varies depending on how they are defined and accounted for. The following subsections provide an overview of each carbon pool, noting their relevance for fire-related GHG emissions and discussing potential definitional discrepancies between IPCC and Swedish reporting.

1.4.1 Living biomass

Living biomass includes all above- and belowground plant material that is alive, primarily trees and understory vegetation. The IPCC defines this as a combination of aboveground biomass and belowground biomass, with emissions occurring when this biomass combusts during fire events (IPCC 2006). The Swedish GHG inventory considers emissions from living tree biomass as the primary component in its forest fire emission estimates, using an assumed 25% combustion assumption. (Naturvårdsverket 2025).

1.4.2 Deadwood

Deadwood refers to non-living woody biomass not contained in the litter layer, either standing or lying on the ground. It is included in both IPCC and NIR definitions, although in practice, its inclusion in emission estimates depends on data availability. IPCC guidelines suggest that deadwood can contribute significantly to emissions during fire, especially when present in large quantities (IPCC 2006). In Sweden's inventory, deadwood is assumed to make up approximately 0.3–0.6% of total forest biomass and is included in the calculation of combusted biomass (Naturvårdsverket 2025).

1.4.3 Litter and Humus

Litter and Humus Litter includes leaves, needles, twigs, and small branches that accumulate on the forest floor. The humus layer, while sometimes considered part of soil organic matter, often overlaps conceptually and functionally with deeper litter horizons, especially in boreal forests. The IPCC defines litter as a separate carbon pool distinct from soil organic matter, whereas Sweden's NIR groups litter and humus together or includes humus in the soil carbon pool. Both litter and humus are highly flammable, particularly under dry conditions, and can contribute significantly to emissions from surface fires. However, they are not explicitly included in the Tier 1 biomass combustion factor in Sweden and are instead assumed to be accounted for through soil carbon pool changes (Naturvårdsverket 2025).

1.4.4 Peat and organic soils

Peat and other organic soils store large quantities of carbon in partially decomposed plant material. Peatlands in Sweden are vulnerable to fire, particularly when drained or exposed during droughts, potentially leading to significant emissions of fossil CO_2 (Naturvårdsverket 2025). Sweden's current forest fire inventory does not include peat combustion in direct emissions, assuming it is instead captured via soil carbon stock changes in the Swedish Forest Soil Inventory (SFSI) (ibid).

1.4.5 Soil organic matter / soil organic carbon

Soil organic carbon (SOC) refers to decomposed biological material incorporated into mineral or organic soils, including residues from plant roots and microorganisms. Under IPCC guidelines, this pool is referred to as soil organic matter (SOM) and forms a distinct category for long-term carbon storage and change assessment (IPCC 2006). Sweden's NIR tracks this pool as soil organic carbon and treats it separately from dead organic matter (DOM), which includes the humus layer (Naturvårdsverket 2025). SOC is generally unaffected by surface fires unless extreme conditions lead to peat combustion. While not considered a direct source of GHG emissions from fire in Sweden's forest fire inventory, any longer-term changes to SOC are captured in the LULUCF sector through national soil monitoring data (IPCC 2006; Naturvårdsverket 2025).

1.4.6 Mineral soils

Mineral soils are composed mostly of inorganic material and form the base of forest soil profiles. They do not store significant amounts of combustible carbon and are not considered a source of GHG emissions in the context of fire. Neither the IPCC nor the Swedish GHG inventory attributes fire-related emissions to mineral soil combustion (IPCC 2006; Naturvårdsverket 2025).

1.5 IPCC guidelines

The IPCC provides methodological guidance for GHG reporting from forest fires within its 2006 Guidelines for National Greenhouse Gas Inventories. These guidelines outline a tiered framework (Tiers 1 to 3) which allows countries to choose the level of methodological complexity that fits their data availability (IPCC 2006). Tier 1 methods rely on global default values while higher-tier methods (Tier 2 and 3) work with country-specific data and models. The equation used by the IPCC for forest fire emission calculation is shown in Table 1.

1.6 Current Swedish approach

Sweden currently uses an approach very close to Tier. In this approach, fire emissions are calculated by assuming an average biomass density of 5.78 t C ha^{-1} for productive forest land and applying a fixed combustion factor of 25% which reflects the assumed share of biomass burned during fire events (Naturvårdsverket 2025). Emissions are then estimated using IPCC default emission factors for CH_4 and N_2O, and the resulting values are reported in table 4(IV).

Importantly, while biomass data from the Swedish National Forest Inventory (NFI) is used to calculate carbon stock changes on permanent plots, these estimates are not directly used for CO_2 emissions from forest fires. Instead, the loss of living biomass due to fire is assumed to be captured in the stock change estimates reported under table 4.A.1. As a result, only CH_4 and N_2O emissions are officially reported in table 4(IV), while the associated CO_2 emissions are mentioned in an other place (ibid.). This separation is designed to prevent double-counting but introduces ambiguity about the actual scale and contribution of fires to the national carbon balance.

Given the increasing availability of spatially explicit biomass data in Sweden there is a growing potential to adopt a higher-tier approach. Doing so would allow for a better quantification of fire emissions and informed the following aim and objectives of this work.

1.7 Aim and objectives

The aim of this study is to explore, design, compare, and evaluate multiple methods for estimating GHG emissions from forest fires in Sweden with a focus on living biomass. It also aims to validate these methods through spatial data analysis and field observations. By addressing the following objectives, the study intends to propose improvements for the Swedish GHG inventory and enhance the accuracy of forest fire emissions reporting:

1. Compare Emission Estimation Methods

Quantify differences among the current Swedish method, the IPCC Tier 1 model, and two methods based on national data (county-based area weighted means and a method based on carbon stocks from exact location using Skogliga Grunddata[3]) in terms of GHG emissions.

2. Validate Reported Burned Areas

Assess the accuracy of Swedish Forest Agency data on forest fires by cross-referencing them with MSB (Swedish Civil Contingencies Agency) data on fire incident reports, field visits, remote sensing inspections and findings from the literature to establish an understanding of its fit for the use in future national GHG reporting.

3. Examine Combustion Fraction Assumptions

Evaluate the validity of Sweden's standard 25% living tree biomass combustion factor[4] using qualitative (scorch height, remaining biomass) field measurements.

4. Propose Improvements for the GHG Inventory

Recommend refined methodologies that can improve the estimation of forest fire related emissions in Sweden.

---

[3] Forest Basic Data provided by the Swesih Forest Agency under https://www.skogsstyrelsen.se/skogligagrunddata

[4] Assumption about how much living tree biomass is consumed in a forest fire

2. Materials and Methods

2.1 Study area

This study focuses on forest fire emissions across Sweden. The county of Dalarna was chosen as a case study region. To support the national relevance of the analysis, a spatial overview of fire frequency and burnt area across Sweden was conducted using data from the MSB wildfire incident database. A preliminary heatmap and later also summaries of fire area by county highlighted that Dalarna has experienced relatively frequent and extensive forest fires in recent years. This made the county a good choice for further analysis, as it offered a relatively representative number of fire events to work with.

2.2 Data description and sources

The selection of data sources was guided by their relevance for estimating living biomass, fire occurrence, and burn severity, which are key parameters in GHG emission estimation models.

While this chapter describes all core datasets used in the final analysis, several additional data products were reviewed during the preparatory phase but not ultimately included (namely SLU's maps on Peat, Dead Organic Matter (DOM), and Soil Organic Carbon (SOC)). Certain data products are discussed in greater detail within the corresponding methods sections. The terminology used across datasets is not always consistent, particularly when referring to land types (e.g., "*unproductive forest",* "*other tree-covered land",* "*skogligt impediment*"). To support the reader, a glossary is included in the appendix and is recommended for clarification of recurring terms. The structure of this data chapter follows the functional role of each dataset. First, data sources related to forest biomass and land classification are presented. These are followed by disturbance-related datasets, including forest fire records and forest operations data, which inform the emission estimation and fire impact assessments in later chapters.

2.2.1 NFI biomass (SLU)

The National Forest Inventory, conducted by the Swedish University of Agricultural Sciences (SLU), serves as a central data source for this study. The NFI is a long-term national program that monitors Sweden's forests by systematic field-based observations and has provided official forest statistics since 1923 (Fridman et al. 2014; SLU 2022). The NFI employs a stratified, systematic sampling scheme across all land types, with approximately 12.000 sample plots assessed annually. Plots are either permanent or temporary and are rotated in five-year intervals. Data collection includes tree-level information (e.g., species, height, diameter at breast height), site characteristics, and land use classification (Fridman et al., 2014). Forest land is defined according to the Swedish Forestry Act, distinguishing between productive and unproductive forest land as well as accounting for formally protected areas (SLU n.d.). Biomass estimates in the NFI are based on tree-level measurements, including diameter at breast height, species, and height. These are collected on a network of systematic sample plots. Biomass is not directly measured but imputed using regression-based equations (Marklund 1988). The equations include components to estimate dry biomass for stem wood, branches, and foliage, typically differentiated by species groups such as pine, spruce, and birch. The results are assigned to sample trees and then aggregated at the plot level using ratio estimators (Fridman et al. 2014). These values form the basis for calculating regional and national biomass averages.

For this study, the NFI data on biomass were derived from SLU's statistical database[5]. It was used together with information on forest land from the Swedish Land Survey (see section 2.2.2) for estimating biomass trends, comparison against biomass values calculated in QGIS (QGIS Development Team 2021)from within fire polygons, and for creating a data collection that enabled re-evaluation of the current reporting scheme in relation to current data availability. To ensure consistency between biomass and forest area estimates across different regions and protection statuses, only data reported as "*productive forest land*" (with and without formally protected areas) was considered. Where total forest land was needed, statistics including both productive and unproductive areas were used.

2.2.2 NFI forest land (SLU)

SLU uses the Food and Agriculture Organization's (FAO) definition of forest land as land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ, and not primarily under agricultural or urban land use (FAO 2020). NFI statistics on forest land area used in this study were derived from SLU's statistical database. The classification of land into productive forest, unproductive forest, and other categories follows definitions from the Swedish Forestry Act, §1 (Sveriges Riksdag 1979), with productive forest defined as land capable of producing at least 1 m^3 of wood per hectare per year.

2.2.3 Biomass (Skogliga Grunddata - SKS)

The biomass dataset used in this study is part of the national forest attribute map of Sweden. The raster data is publicly available through the Swedish Forest Agency's (Skogssyrelsen, SKS) geodata portal under "Skogliga grunddata" (Skogsstyrelsen 2025c). The biomass map provides estimates of above-ground tree biomass in tonnes of dry matter per hectare (t dry matter ha^{-1}) These estimates include stem wood, branches, and tops but exclude stumps and roots (Nilsson et al. 2017). Raster cells have a spatial resolution of 10 × 10 m and, once finalised, cover all of Sweden's forest land. Values are only reported for pixels where the basal area-weighted mean tree height exceeds 3 metres. All values below this threshold are set to zero, typically indicating very young forests, regenerating areas, or non-forested land (Skogsstyrelsen 2025c). The 2022 version, which is already the first updated version of this product, is used for this study.

The estimates were produced using co-processing of airborne laser scanning (ALS) data and data from field plots from the NFI. The ALS campaigns were conducted between 2009 and 2015, with a point density of 1.0 points per square

[5] https://skogsstatistik.slu.se/pxweb/en/OffStat/

metre. Forest variables were derived using linear regression models calibrated with 10 m radius NFI plots, which were spatially aligned with ALS data and temporally adjusted through forecasting or backcasting using the Heureka forest planning system (Wikström et al. 2011; Nilsson et al. 2017). To ensure reliable matching of ALS and NFI data, plots with disturbance between scanning and field visit or strong mismatches in tree height (>5 m difference between measured and ALS-derived height metrics) were excluded (Nilsson et al. 2017). Regional models were developed for different ALS blocks using the 350 nearest NFI plots, which prioritised predictors such as canopy height percentiles, canopy cover, and vertical variability. The reported accuracy of biomass estimates is a relative RMSE of approximately 25% at the plot level, which is consistent with other national forest mapping efforts (Nilsson et al. 2017). Map accuracy is highest in conifer-dominated, well-managed forests and lower in broadleaf stands. Scanning in leaf-on season may lead to overestimation of biomass due to laser pulses being intercepted in the crown (Skogsstyrelsen 2025c). Conversely, underestimation may occur in leaf-off scans.

Since the biomass estimates reflect the forest condition at the time of scanning, the map needs to be temporally adjusted for better accuracy of biomass. In this study, ALS-derived biomass values were adjusted to a common reference year (2021) using average regional growth rates from the NFI and corrected for disturbances such as harvests and wildfires occurring after the scan (see section 2.5.2).

2.2.4 National land cover map (SEPA)

The National Land Cover Map (Nationella Marktäckedata, NMD) is a raster-based thematic land cover classification produced by the Swedish Environmental Protection Agency (Naturvårdsverket, SEPA) in collaboration with many Swedish authorities. The product provides wall-to-wall coverage of Sweden at 10 x 10 m spatial resolution and is primarily based on Sentinel-2 satellite imagery from the vegetation season of 2018 (Naturvårdsverket 2020). A newer version from 2023 is available but not used as the classification was not complete for some regions at the time of data acquisition (February 2025).

The NMD classifies land into 25 categories based on a Swedish adaptation of the CORINE Land Cover standard. Forest-related land cover types are differentiated into productive and unproductive forest, shrubland, wetlands, and other open or semi-natural areas. In addition to the base map, there are complementary layers available, describing object height and extent, productivity, and land use in mountainous regions (Naturvårdsverket 2020). Accuracy assessment of the NMD product has shown it to be high when compared with field data from NFI and the National Inventory of Landscapes in Sweden (NILS). For broad land cover categories (e.g., forest, wetland, open land), overall classification accuracy reaches 94–95%, depending on region. For more detailed classes, it remains above 70% across most regions, though specific forest subclasses (e.g., mixed deciduous forests) showed lower producer and user accuracy in some cases (Nilsson et al. 2020). Limitations of the NMD include temporal mismatches between satellite acquisition and field data, classification challenges in sparse or transitional vegetation zones, and sometimes confusion between similar classes like shrubland vs. young forest (Nilsson et al. 2017). In this study, the NMD was employed to create a forest land mask to get biomass values only for forest areas, relevant for further creating a harmonised biomass map.

2.2.5 Fellings carried out (Skogliga Grunddata - SKS)

To correct biomass layers for disturbance, this study explored the dataset on fellings carried out "Utförd avverkning" from SKS. It contains spatial polygons of logging activities throughout Sweden. It includes information such as type of felling, date of felling, responsible party, and area (Skogsstyrelsen 2024). In the context of this study, the data was considered potentially valuable for identifying areas where biomass estimates from the ALS-derived forest biomass map from Skogliga Grunddata might be outdated if harvesting had taken place in the meantime. Especially fire polygons that overlapped with clear-cuts occurring between the time of ALS scanning and fire occurrence would need to be corrected for to avoid overestimation of pre-fire biomass and related GHG emissions.

Unfortunately, limitations in the consistency and interpretability of the dataset limited its usability for statistically relevant quantitative analysis. Metadata such as the exact date or type of felling is sometimes missing or recorded in inconsistent formats. This led to difficulties in consistently aligning felling polygons with ALS scan dates and fire event timelines across the dataset. According to the product description, the dataset is not a comprehensive inventory of all fellings in Sweden but should rather be used as a guiding basis.

As a result, while individual examples could be reviewed manually, it was decided that a national-scale correction of biomass using this layer was not feasible within the scope of this thesis. Nevertheless, a decision matrix was developed to guide disturbance correction (Table 3), but full implementation within the framework of this thesis was halted due to these quality issues.

2.2.6 Wildfire event database (MSB)

To assess the national extent of forest fires and validate other spatial fire data sources, this study used the annual wildfire event database maintained by the Swedish Civil Contingencies Agency (MSB). The database, which is the main source to estimate the annual wildfire area used in Sweden's national GHG inventory, compiles incident data from municipal fire departments. Since 2020, the dataset also includes georeferenced records for every incident and has become suitable for spatial comparison.

Each record represents a distinct fire incident and includes the following attributes:

- Event date
- Municipality name and ID
- Coordinates (SWEREF99 TM) representing either the initial location reported to SOS Alarm or a point manually relocated by fire personnel (often the vehicle position)
- Burnt area in m^2 distributed across land cover classes:
    - Productive forest land (including felled areas)
    - Other tree-covered land
    - Arable land or pasture
    - Other open land without tree cover

The spatial resolution of the dataset is limited to a single coordinate per fire event. While it includes estimates of burnt area by land type, these are reported by the municipal fire departments using varied methods (i.e., GPS measurements, aerial observations, map-based estimations, and personal reports). The choice of method depends largely on local practices and the size of the fire, with larger fires typically receiving more precise assessments, while smaller events may rely on rougher estimates (MSB 2024a). MSB itself does not revise incident records but provides feedback to fire departments when discrepancies are suspected. Subsequent amendment of these records is the responsibility of the reporting municipalities and is not done by MSB. In general, MSB follows up on fires affecting land or forest areas if the reported burnt area exceeds 1 hectare or if the fire lasted more than one day. Since 2018, improved reporting logic and routine follow-ups have significantly increased data reliability (MSB 2024b).

Despite these mechanisms, a range of challenges related to systematic uncertainties remain (Granström 2023). These include:

- Variation in coordinate accuracy due to subjective location marking, often the spot where the emergency call was made or the location the first fire truck parked
- Differences in the way area estimates are carried out
- Possible underreporting, although significantly improved since 2018 due to new reporting system logic and follow-up routines

In this study, the MSB database helped to explore different fire categories and their occurrence across the spatial and temporal scale. Subsequently, it served as a reference dataset to assess the completeness and accuracy of the fire polygons derived from Skogliga Grunddata. The MSB coordinates were further used in QGIS for proximity analysis with SKS polygons to assess temporal-spatial correspondence, with a specific focus on productive forest land fires.

Also, the meaning of the terminology "*other tree-covered land*" was explored to better align the events with fires in the reporting scheme of productive forest, unproductive forest, and no tree cover. Even though a technical definition of MSB could not be obtained, data compiled in an SLU report suggests that the term refers to sparsely wooded land with low productivity – generally land that yields less than 1 m^3 of wood per hectare per year (Ramberg 2017). This would be in line with Sweden's official definition of unproductive forest land (Swedish Forestry Act (1979:429) §1). Also, the Swedish Statistical Yearbook of Forestry (2014) defines unproductive forest land as including both unproductive forest land and tree- and shrub-covered land that does not meet forest criteria (Skogsstyrelsen, 2014). The land cover category "*other tree-covered land*" thus seems to include both of these low-productivity wooded areas outside the productive forest definition.

2.2.7 Fire polygon dataset (Skogliga Grunddata - SKS)

To obtain information on spatial extent, geopositioning, and fire type on burnt forest areas across Sweden, this study used the forest fire polygon dataset provided by the Swedish Forest Agency. The dataset's purpose is to inventory, delineate, and classify forest fires in support of environmental monitoring, forestry planning, and reporting to national and EU-level authorities (Skogsstyrelsen 2025a). The dataset consists of manually delineated polygons derived from satellite image comparisons. For fires in 2018, mapping was based on incident reports compiled by MSB and supplemented with pre- and post-fire satellite imagery. In some cases, aerial images were also used. From 2019 onwards, SOS Alarm (a company operating the emergency number 112 in Sweden) coordinates were used as a starting point for identifying burnt areas through visual comparison of pre- and post-fire satellite images. All mapped polygons represent the outer boundary of visible fire impact, and no masking of unaffected internal patches was applied. The mapped area may include non-forest land types (Skogsstyrelsen 2025a).

In the dataset, starting in 2020, each fire polygon has been categorised into one of the following fire types or labelled:

- Wildfire
- Nature conservation burnings
- Regeneration burnings

Where this information was not available, the polygon was labelled instead with "Missing information". Starting in 2023, the delineation and classifications of the biggest fires have been validated against MSB's wildfire database (Skogsstyrelsen 2025b). Although the dataset provides detailed spatial coverage, it does not include fires with minimal visual impact that cannot be spotted on satellite imagery or are too small to find (mostly areas smaller than approximately 0.5 hectares) (Skogsstyrelsen 2025a). Additionally, quality assurance is performed continuously, and already-published polygons may be updated or removed if found to have an error (Skogsstyrelsen 2025b). One such error was identified during this study's field validation and later acknowledged and corrected by SKS.

Two versions of the Swedish Forest Agency's fire polygon dataset were used in this study. The first version (referred to from here on as v.1), covering the years 2018–2024, was provided by thesis supervisors at the beginning of the project. The second version (referred to from here on as v.2) was accessed in April 2025 via the publicly available REST API from SKS and includes data from 2018 to 2025.

Which version was used in which method is stated in the corresponding section. The polygon data were used for:

- Quantifying burned area per year, per county, and per fire type
- Comparing fire area totals with MSB data
- Calculating mean and area-weighted biomass per fire polygon using the Zonal Statistics tool in QGIS
- Performing proximity and overlay analyses with MSB fire report points in QGIS

While both datasets contain similar polygon geometries, only the first version included fire type classifications (e.g., wildfire, regeneration burn, nature conservation burn) and event dates, which were missing in the REST API layer at the time of analysis.[6]

2.3 Validation of reported burned areas

For the validation of the burnt area, two different approaches were used, depending on if it concerned wildfires or controlled burnings. Field visits were done for both fire types, with a focus leaning towards wildfires to supplement the dataset comparison with qualitative ground truthing. Six fire sites in Uppsala and Dalarna were therefore visited in spring 2025 (see also 2.4). At each site, the fire area was located using smartphone GPS with an imported coordinate pin, previously exported from the fire polygons in QGIS. Photos and notes were collected to help interpret if the mapped polygon accurately captured a burnt area.

2.3.1 Wildfires

To assess how consistent and reliable the fire area data provided by SKS was, it was validated against the national wildfire database from MSB and field observations. Of interest here especially is how good they are at capturing a significant enough proportion of the total burnt area to justify the use of biomass values derived from the polygon areas. The validation focused on identifying potential spatial mismatches as well as misclassification and event timing, with a focus on productive and unproductive forest areas.

Comparison with MSB fire incident data

The MSB wildfire incident database, which contains georeferenced point data for individual fire events, was used to evaluate the completeness and consistency of the polygon-based burnt area data provided by SKS. For the years 2018–2024, the total burnt area and number of fires reported by MSB were aggregated per county using Microsoft Excel based on municipality codes and available land cover classifications. Only fires classified by MSB as occurring in “productive forest land” or “other tree-covered land” were included for comparison with the forest-relevant SKS polygons. To assess the completeness of the SKS datasets, fires of all sizes from the MSB dataset were kept for the comparison. An exclusion of fires <

[6] This was reported to SKS but could not get fixed in time to do the performed analysis again.

0.5 ha would have enabled the comparison of estimation performance, but this was not done. The focus of the analysis was put on the assessment of the absolute area difference to validate how much fire area would be lost if SKS alone were used as a data source.

Corresponding statistics (burnt area and fire count) were calculated from the SKS polygon dataset (v.1) using QGIS. The SKS polygons were first clipped to county boundaries, and the "Join attributes by location (summary)" tool was used to calculate total burnt area and number of polygons per county and year. These outputs were then exported for comparison with the MSB-derived tables in EXCEL.

Later, also, the new version of this dataset (v.2) was used. This was motivated by a discrepancy identified during correspondence with MSB[7], suggesting the probability that the total burnt area in the calculations of this thesis did not match their official figures. A comparison was then conducted between SKS v.2 and MSB data at the county level for the available years 2020–2024, which revealed a significant mismatch for 2023. To investigate this further, the largest fire polygons in 2023 were inspected in QGIS, and the absence of correct event dates in the v.2 attribute table was identified as the cause of this discrepancy. These observations motivated the exclusion of version v.2 from use in the final results on the per-fire biomass.

Spatial proximity analysis with MSB coordinates

Because the MSB database contains only a single coordinate point per fire event, a spatial comparison was conducted in QGIS to assess how well the reported MSB points corresponded to the SKS polygon locations. This was motivated by a specific observation during fieldwork: one SKS polygon, classified as a wildfire, showed no visible burn damage. The closest MSB point was measured using QGIS's distance tool and inspected for additional attributes. This type of proximity analysis was repeated for a selection of other fire polygons from 2024 to determine whether point-based reporting by MSB tended to systematically diverge from the delineated fire area.

2.3.2 Controlled burnings

The official NIR-reported areas of controlled burnings as inventoried by SKS (Naturvårdsverket 2025) were compared against data on the same issue compiled by Ramberg et al. (2018). This was done, as it was not clear how many of the surveyed fire areas SKS really manages to delineate. Also, with the limitation of the biomass map in mapping forests with an average tree height < 3 m (so especially problematic for regeneration burn areas), the focus of this study was therefore moved in the direction of assessing if the reported tabular data can be considered complete or should rather be questioned.

[7] Based on e-mail communication with Frida Carlstedt

2.4 Examination of combustion fraction assumption

To assess the validity of the 25% combustion fraction assumption currently applied in Sweden's national GHG inventory, field observations were conducted at six selected fire sites in Uppsala and Dalarna in spring 2025. The objective was to evaluate the extent of living tree biomass combustion in real post-forest-fire conditions.

Site Selection:

- Two recent wildfires in productive forest
- Two nature conservation burnings in protected forest areas
- One wildfire in protected forest area
- One wildfire in unproductive forest

Assessment:

- Visual inspection of fire extent and surrounding landscape
- Assessment of tree scorch height
- Rough evaluation of ground fuel combustion (moss, humus, and litter layers)
- Estimation of affected aboveground living tree biomass
- Notes on burned deadwood or peat layer and post-fire vegetation recovery
- Photo documentation

2.5 Biomass estimation for emission calculations

To assess fire available fuel, two approaches where taken. First, forest mask was created to mask the ALS-derived biomass map from Skogliga Grunddata. The resulting product was then corrected for forest growth. Second, NFI data on forest biomass was compiled or calculated as difference to present biomass values and, where applicable, trends for every available forest land category. Both products where then compared to the biomass assumption currently used in Sweden's National Inventory Report (Naturvårdsverket 2025) and assessed for their usefulness in future reporting.

2.5.1 Forest mask

To ensure that biomass and emission calculations were restricted to forest land, a binary forest mask was developed using the National Land Cover Map (NMD) (see section 2.2.4). The purpose of this mask was to exclude non-forested areas from the ALS-derived biomass raster map provided under Skogliga Grunddata (see section 2.2.3) to be able to create a harmonised biomass map by performing raster calculations on only forest biomass-related pixels.

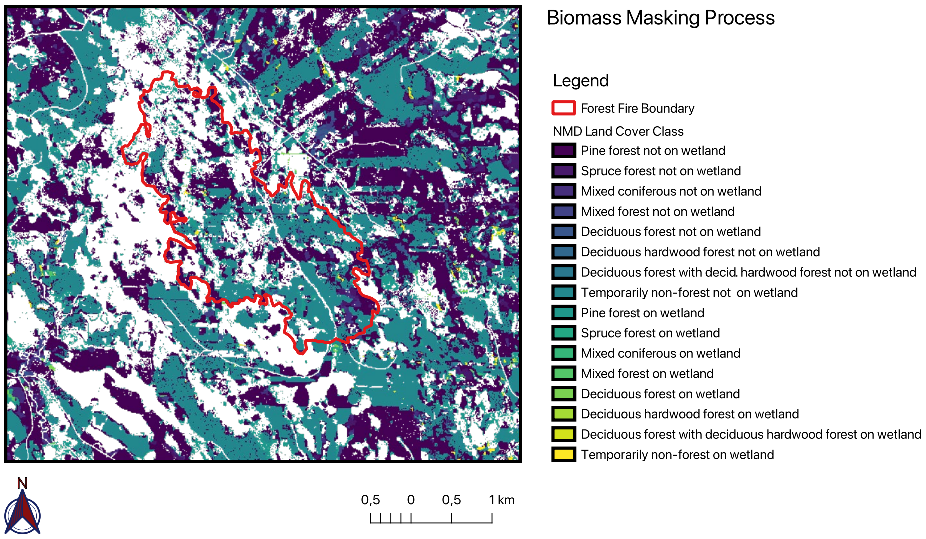


Figure 1. Forest mask produced from NMD Land Cover Map. Only forest classes were retained for biomass analysis. SKS fire boundaries shown for illustrational purposes on a real case.

For this study, forest land was defined as all land cover classes between 111 and 128 (see Appendix1, Table 6), which include coniferous, broadleaf, and mixed forests of varying productivity (Naturvårdsverket 2020). Class 42 ("vegetated other open land") was excluded, in contrast to the convention of the national GHG inventory, to focus strictly on clearly forested areas, the focus of this study.

The forest mask was created in R (R Core Team 2024) using the terra package (Hijmans 2025). First, NMD raster were cropped and masked by county boundaries to reduce data size and memory load. Then, each county-level NMD raster was reclassified using a rule matrix to create a binary mask: pixels in the forest class range (111–128) were assigned a value of 1, while all other classes were set to NA. As shown in Figure 1, the output raster contained only forest biomass and were stored per county for processing in later steps. This binary forest mask was then used to filter the national biomass raster from Skogliga Grunddata. The mask function from terra (Hijmans 2025) was applied to retain biomass values only in forest-classified pixels. A consistent NAflag value of -9999 was used across all masked layers for interoperability in QGIS and R. This specific value was chosen, as it was likely to not conflict with true values that might occur.

To assess the reliability of the forest mask created from the NMD data, several validation steps were carried out. These included comparisons of biomass estimates derived from masked raster values with statistics from Sweden's official forest inventory and statistical reporting platforms. A key test area was Dalarna, for which biomass was extracted from the masked raster and compared with NFI data, using the biomass raster masked with NMD classes 111–128 and assuming 50% of living biomass is carbon.

The resulting forest-only biomass raster was used as input for analysis, including growth correction of ALS-derived biomass to a 2021 reference year (section 2.5.2), intersection with SKS fire polygons to determine available biomass in burnt areas (section 2.5.3), and per-county extraction of forest carbon stocks and fire-specific emissions.

2.5.2 Biomass raster correction

Biomass correction using forest growth

The ALS-derived biomass raster provided by the Swedish Forest Agency (Skogsstyrelsen) reflects forest conditions at the time of data acquisition, which occurred between 2018 and 2022 depending on region (Figure 2). To enable consistent comparison of fire-affected biomass across years, this study corrected all pixel values in the biomass raster created in this project to a common reference year of 2021. The process of temporal harmonisation was necessary to avoid systematic over- or underestimation of available biomass in fire polygons scanned in different years. This normalisation was conducted in QGIS for the case study in Dalarna, where the original biomass raster and associated ALS metadata were first clipped to the county extent. A raster of ALS acquisition years was derived by extracting the year field from metadata using expressions and rasterising it at a 10 × 10 m resolution to match the biomass raster grid. The two raster were aligned and overlaid using the Raster Calculator to apply a year-specific biomass growth correction. A linear approximation of biomass change was done, using equation 1:

$$biomass_{2021} = biomass_{ALS} \times \left(1 + 0.035 \times \left(2021 - ALS_{year}\right)\right) \quad (1)$$

This equation assumes an average annual growth rate of 3.5%, derived from regional data provided by the NFI (see Appendix 1, Table 5)The correction was applied both forward and backward in time to align all pixel values with the biomass levels expected in 2021. This linear growth model is a simplified but reasonable choice for harmonising biomass over short time periods, especially in mature forests. An exponential correction was also tested, using equation 2:

$$biomass_{2021} = biomass_{ALS} \times (1 + 0.035)^{(2021-\text{ALS year})} \quad (2)$$

The age structure of Dalarna's forest is, for the most part, in the early, exponential growth phase. A report from Länsstyrelsen (2021) shows that most of the forest stands are between 0 and 40 years old. Most of the biomass growth is thus found in rather young stands, which are in an exponential growth phase (Repo et al., 2021). Nevertheless, the exponential model would have the risk of disproportionately increasing biomass in these old stands – where the growth curve is actually not that steep anymore – while failing to account for biomass accumulation in young forests, which are excluded from the raster entirely due to the 3-metre minimum tree height filter (Skogsstyrelsen, 2025c). These stands are mapped as zero biomass and would remain unaffected by any correction. Statistical comparison proved that the difference between linear and exponential correction was negligible over the short time span relevant for most of Dalarna. The mean biomass increased from 68.52 t dry matter ha^{-1} (original raster) to 68.70 t dry matter ha^{-1}, which is about 1.75% or 1.18 t dry matter ha^{-1} with the linear model, and to 68.74 t dry matter ha^{-1} with the exponential model, which is only a minor increase of 0.06%. Given these limitations and insignificant changes, the linear correction was used in further calculations.

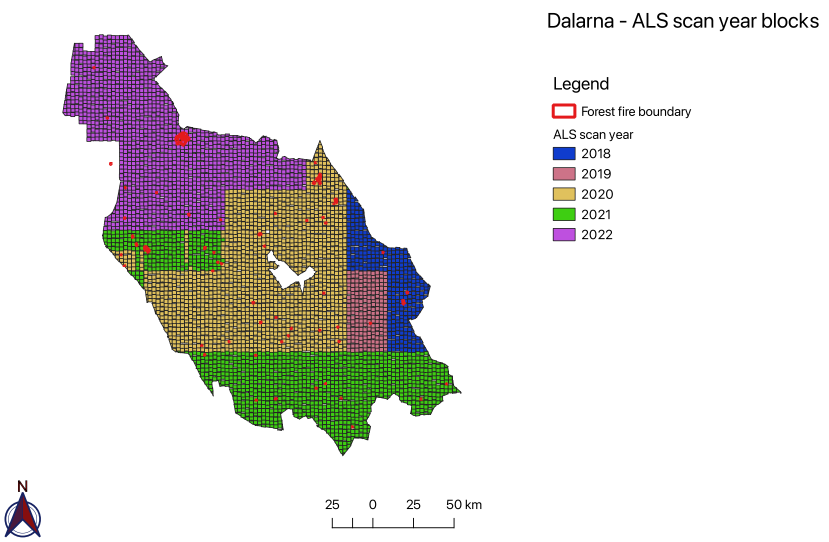


Figure 2. Map showing blocks with the corresponding year for which an area in Dalarna had been ALS-scanned and fire polygons for the years 2018-2024.

The derived increase of the biomass also seems reasonable when examining Figure 2. The most productive areas of Dalarna had been scanned between 2018 and 2021; the less productive mountainous region was scanned in 2022. The biggest share of Dalarna had only been forecasted for one year (2020-2021); another big area was neutral for the calculation (2021); the big, mountainous, and less productive area had been backcasted for one year (2022-2021); and two rather small parts for 2018 and 2019 had to be forecasted for 2 and 3 years, respectively. So, the 1.75% growth from the patched map to the reference year 2021 seems reasonable.

The resulting raster, corrected to 2021, was then used in further analyses. For transparency, this approach is acknowledged as a simplified growth approximation that could be refined in future work using dynamic growth modelling tools such as the Heureka system (Wikström et al. 2011; Nilsson et al. 2017).

Biomass correction using disturbance data

Following the growth correction process, a method was developed to account for post-scan disturbances (i.e., wildfires and forest operations) that might have altered forest biomass after the ALS data collection. Inspired by procedures outlined in Nilsson et al. (2017), the aim was to identify pixels where ALS-derived biomass values were likely overestimations due to unrecorded losses between scan and fire years. To achieve this, all relevant temporal information needed to be rasterised at 10 × 10 m resolution. This included the ALS scan date (from the metadata of the biomass map), the forest operation date (from the attribute table of the fellings map), and the fire date (from the attribute table of the polygons from Skogliga Grunddata v.1). To achieve this, information availability needed to be harmonised. Especially as the exact day of fire events was lacking for a lot of fire polygons (particularly for those prior to 2021), an approach was used to approximate these. This was chosen over exclusion of the fires, as this would have eliminated the use of some of the biggest fires in the database. So, the approach taken was to calculate the median day of the year for fire occurrence and use that in combination with the year of the respective occurrence, which was known for all fires. It was calculated using the national fire event database provided by MSB for the years 2020 to 2023, as this source had the most fire events recorded and always a data point assigned to it.

The dataset originally included 18.407 fire events for the time span observed, of which 3.353 occurred on productive forest land. These were filtered and aggregated, and the day of the year (DOY) was computed for each valid date. This allowed the comparison of fires across years on a common ordinal scale. The median DOY for fire occurrence in Sweden was found to be 167, which is June 15. This date was then translated back to the normal date format for further use in QGIS. There, to apply this proxy in raster-based calculations, a standardised integer date format of the form YYYYMMDD was used to fill raster burn-in values for date alignment. For records with full fire dates, a new field was created in the attribute table. For records with no date but with a valid year field, the proxy date June 15 was assigned. These were then combined in a single column. These cells, with either the exact or proxy date, were then used as the burn-in value in the process of rasterising the fire polygons at 10 m resolution and used as the temporal reference layer in the disturbance logic that aligned biomass, fire, and forest operation dates at the pixel level.

With the reference layer at hand, a pixel-wise decision matrix (see Appendix 1 Table 3) was designed to adjust biomass values for the chronological order of disturbances relative to the scan. For example, if a forest operation occurred after the ALS scan but before a fire, biomass in those pixels would be set to zero. Where only fire occurred after the scan, biomass was reduced to 75% of the ALS-derived value, based on the default assumption of a 25% combustion factor in the Swedish GHG inventory.

Despite constructing and testing this logic, the correction was not implemented in the final biomass raster. The corrected biomass raster used in subsequent analyses reflects biomass correction via growth only, without incorporating disturbance effects.

2.5.3 Intersection of biomass raster with SKS polygons

To arrive at the biomass available for combustion during wildfires within the delineated fire polygon area, this study intersected the biomass raster that was harmonised for 2021 with forest fire polygons from the SKS dataset (v.1). The data acquired was then processed in Microsoft Excel to calculate the growth-corrected mean biomass per hectare of fire area per year. The analysis was limited to Dalarna and covered fires that occurred between 2018 and 2024. The objective was first to determine the mean biomass per hectare (t dry matter ha^{-1}) for each individual fire polygon, adjusted to the reference year 2021.

The procedure was carried out in QGIS as follows:

- The SKS fire polygon dataset was clipped to the boundary of Dalarna.
- The 2021-corrected biomass raster, which had previously been masked to forest areas using the National Land Cover Map (section 2.2.4), was clipped to the same extent.
- Using the Zonal Statistics tool, the mean biomass per hectare (t dry matter ha^{-1}) was calculated for each fire polygon. This operation generated a table with the mean biomass value for each fire geometry.
- The resulting attribute table was exported to Excel

In Excel, the biomass values were adjusted to the actual year the fire occurred to reflect the forest's growth between the time of ALS scanning and the fire event. The adjustment was done using a linear growth rate of 3.5% (equation 3) per year, following the logic laid out in section 2.5.2:

$$biomass(year_{fire}) = biomass_{2021} \times \left(1 + 0.035 \times \left(year_{fire} - 2021\right)\right) \quad (3)$$

These polygon-level, fire-specific biomass values (in t dry matter ha^{-1}) were subsequently used to calculate GHG emissions from forest fires (see Section 4). They formed the basis for a refined emission estimation method, which was later compared against

- The IPCC Tier 1 default method,
- The Swedish Tier 1 method, and
- A method based on county-level weighted biomass averages from compiled NFI data.

2.5.4 Compiling NFI data for a biomass trend assessment

The second source of biomass information was the NFI. Information was gathered to evaluate how representative the biomass assumptions in Sweden's current GHG reporting scheme are and to provide alternative, spatially more detailed values for emission estimation. The following steps were taken:

Biomass per hectare values were collected for as many years as possible for the period 1985–2021 for the following forest categories:

- Productive forest excl. protected areas
- Productive forest incl. protected areas
- Productive forest and unproductive forest incl. protected areas excl. alpine regions
- Productive forest and unproductive forest incl. protected areas incl. alpine regions
- Unproductive forest incl. protected areas incl. alpine regions

Where the biomass was not explicitly available from the NFI, it was calculated with the help of total biomass and biomass from other categories, as well as with information on different forest land area values. Results were visualised in Excel using a line chart. These trends were used to assess the potential need for a regularly updated biomass value in GHG emission calculations from forest fires.

2.6 Emission estimation methods

To estimate GHG emissions from forest fires, this study applied and compared four different estimation approaches. An overview of the formulas and parameters used in this study is provided in Table 1. The IPCC Tier 1 approach is based on equation 4, with formula and parameters being obtained from IPCC (2006) Guidelines for National GHG Inventories (IPCC 2006). Equation 5, which served as a basis for all Swedish methods tested, was derived from the Swedish National Inventory Report: Annexes . The formula is shown in an adapted form for better comparison with the IPCC equation. For the Tier 1 method, parameters are derived from the same source (ibid.). For Tier 2 methods, fuel biomass values got adapted to either a national average (Swe2-N) or a county-based area-weighted mean value (Swe2-CB) – see Table 2.

All methods focused on estimating the emissions of CO_2, CH_4, and N_2O from the combustion of aboveground living biomass. Conversions to CO_2-equivalents were done using Global Warming Potential (GWP) values for the 100-year time horizon from the IPCC Fifth Assessment Report (AR5) (Myhre et al. 2013): 1 for CO_2, 28 for CH_4, and 265 for N_2O. These values were chosen to be consistent with Sweden's current national GHG inventory methodology even though newer values are available since IPCC's Sixth Assessment Report (AR6) (Forster et al. 2023). These will become relevant for future emission reporting.

Each method used the same principle: emissions are a function of the burnt area, the amount of biomass available for combustion, and the assumed combustion and emission factors. However, the equations they are based on differ in two main ways: Firstly, while the IPCC uses a combustion factor assumption of 0.34, Sweden uses 0.25. Secondly, while the IPCC uses gas specific emission factors to convert from dry matter to the amount of gas emitted, Sweden uses an approach with explicit values for carbon fraction, density and molar weight.

Table 1. Equations used for estimating GHG emissions from biomass burning under different methodological approaches

Method	Equation	Eq.	Parameters
IPCC Tier 1 (IPCC1)	$E_{gas} = A \times M_B \times C_f \times G_{ef} \times 10^{-3}$	(4)	$M_B = 41$[t dry matter ha^{-1}] $C_f = 0.34$ $G_{ef(CO_2)} = 1569[g\ kg^{-1}]$ $G_{ef(CH_4)} = 4.7\ [g\ kg^{-1}]$ $G_{ef(N_2O)} = 0.26\ [g\ kg^{-1}]$
Swedish Tier 1 and Tier 2 (Swe1, Swe2-N, Swe2-CB)	$E_{gas} = \mathrm{A} \times \mathrm{M}_B \times C_{frac} \times C_f \times \mathrm{R_{gas}}$	(5)	$M_B(Swe1) = 46\ [t\ dry\ matter\ ha^{-1}]$ $M_B(Swe2 - N) = 91[t\ dry\ matter\ ha^{-1}]$ $M_B(Swe2 - CB) = per\ county\ from$ Table 2 $C_{frac} = 0.5$ $C_f = 0.25$ $R_{gas(CO_2)} = 44/12$ $R_{gas(CH_4)} = 0.012 \times 16/12$ $R_{gas(N_2O)} = 0.01 \times 0.007 \times 44/28$

E_{gas}: Emissions per gas [t]
A: Burned area [ha]
M_B: Fire available fuel biomass [t dry matter ha^{-1}]
C_f: Combustion factor i.e., fraction of biomass consumed during fire
C_{frac}: Carbon fraction i.e., how much of biomass is carbon
G_{ef}: Emission factors
R_{gas}: Stoichiometric ratios

2.6.1 IPCC Tier 1 default method (IPCC1)

In the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006), a generic equation (see Table 1, eq. 4) for calculating emissions is given, using standard emission factors for each gas. Those allow for the direct conversion from dry matter to gas emissions without having to rely on stochiometric ratios. A combustion factor of 0.34 and a default biomass value of 41 t dry matter ha^{-1} for boreal forests is used. This method assumes no litter or dead wood combustion unless a land-use change occurs and uses globally averaged constants (ibid.). Emission factors for "extra tropical forests" are used, as recommended by the guidelines.

2.6.2 Swedish Tier 1 method: current national inventory approach (Swe1)

Sweden's current GHG reporting method (Table 1, Eq. 5 with $M_B(Swe1)$) uses a national average biomass value for productive forest land 46 t dry matter ha^{-1}, combined with gas-specific stochiometric ratios, based on density and molar weight, for CO_2, CH_4, and N_2O, as presented in the former IPCC guidelines (IPCC 2003). The method assumes a combustion factor of 0.25 for aboveground biomass (ibid.) This approach is used in Sweden's reporting under the LULUCF sector to the UNFCCC and EU (Naturvårdsverket 2025).

2.6.3 Swedish Tier 2 method: continuously updated national average (Swe2-N)

The Swe2-N method (Table 1, Eq. 5 with $M_B(Swe2 - N)$) is using an updated national average biomass value 91 t dry matter ha^{-1} (derived from the most recent NFI data. If implemented as a Tier 2 method, it would be updated for every GHG inventory. In this thesis, it utilises a recalculated national mean for productive forest land based on official NFI data from the year 2021 (see national average in Table 2). As NFI is always a 5-year average, this is the most recent value available at the time of writing (June 2025). To obtain the updated biomass factor, NFI estimates of aboveground dry biomass per hectare for all productive forest land (including protected areas) were used. All other assumptions remained the same as with the Swe1 method.

2.6.4 Swedish Tier 2 method: county-based area-weighted average (Swe2-CB)

This method uses county-level biomass data compiled from the NFI database available from SLU (SLU n.d.) with the similar equations from Table 1 (Eq. 5) to the Swedish Tier 1 approach, adjusted for productive forest area (Table 2). Biomass values (in t dry matter ha^{-1}) were converted to carbon (t C ha^{-1}) by multiplying by 0.5, and the combustion factor of 0.25 was applied to estimate the amount of carbon burnt. In this study, the method using NFI data from a high fire year (2018) and a normal fire year (2021).

Table 2. Values represent average aboveground dry matter biomass per hectare as reported by NFI for each county in 2018 (average 2016-2020) and 2021 (average 2019-2023). Biomass values reflect productive forest land incl. protected areas. National average is shown for reference. These data were used in the county-based emission estimation method (Swe2-CB).

County	2018 [t dry matter ha^{-1}]	2021 [t dry matter ha^{-1}]
Stockholm	116	107
Uppsala	106	95
Södermanland	102	93
Östergötland	99	95
Jönköping	94	97
Kronoberg	82	85
Kalmar	98	94
Gotland	85	80
Blekinge	120	113
Skåne	108	110
Halland	115	107
Västra Götaland	110	106
Värmland	93	91
Örebro	94	95
Västmanland	92	92
Dalarna	72	75
Gävleborg	80	80
Västernorrland	84	83
Jämtland	81	81
Västerbotten	68	70
Norrbotten	65	67
National Average	93	91

3. Results

3.1 Validation of reported burned areas

This section presents results from the validation of burnt area data in Sweden's national GHG inventory. The analysis distinguishes between wildfires and controlled burnings (including regeneration and conservation burnings), which are treated separately in the Swedish reporting scheme. The primary goal was to assess the spatial completeness and consistency of the SKS fire polygon datasets by comparing them to event records from the MSB, as well as to explore uncertainties in reporting on controlled fires.

3.1.1 Wildfires: polygon validation against MSB database

To validate fire polygons from SKS, two versions of the fire polygon dataset (v.1 and v.2) were compared to the MSB wildfire incident database. The MSB dataset, which includes all fire incidents reported by municipal fire departments since 2020, was used as a reference baseline. For each year between 2018 and 2024, the total number of fires and the summed burnt area were calculated from both SKS versions and compared to MSB using relative difference measures (Figure 3 and Figure 4.

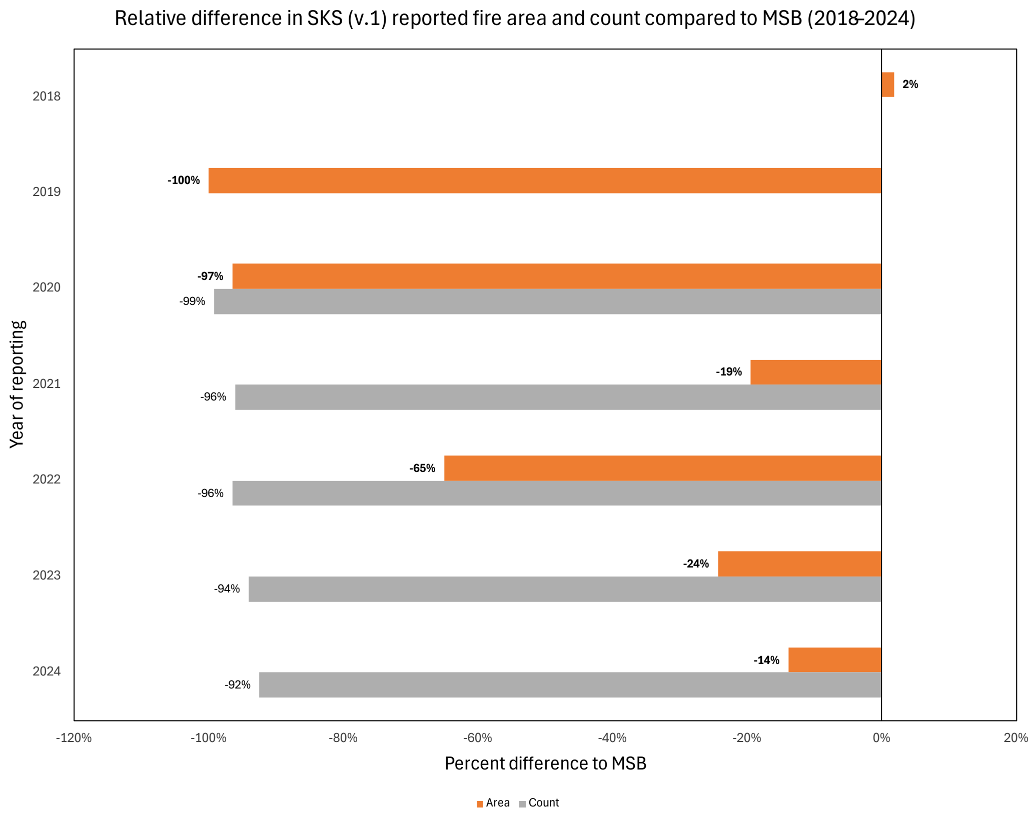


Figure 3. Relative difference in burnt area and number of fire events between MSB and SKS v.1 datasets for the years 2018–2024. For 2018 and 2019, MSB reported only total area, so no information on count is available.

Figure 3 shows the relative difference in reported fire area and fire count between SKS v.1 and MSB. The results indicate that SKS v.1 better approximates total burnt area than it captures the number of fire events. For 2018, which is the first year with substantial polygon coverage, SKS v.1 slightly overestimated fire area relative to MSB. However, for 2019, SKS reported no fire polygons at all. From 2021 onwards, apart from 2022, area estimates in SKS v.1 increasingly come closer to MSB values, which suggests an improvement in findings and delineating fires over time.

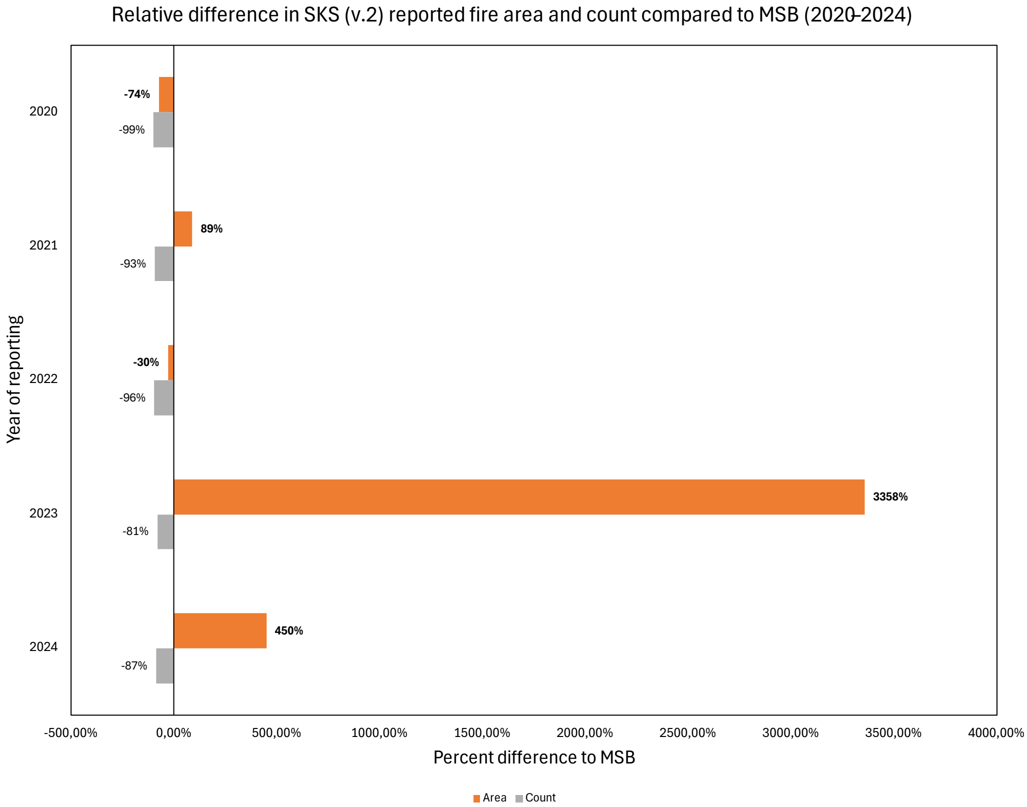
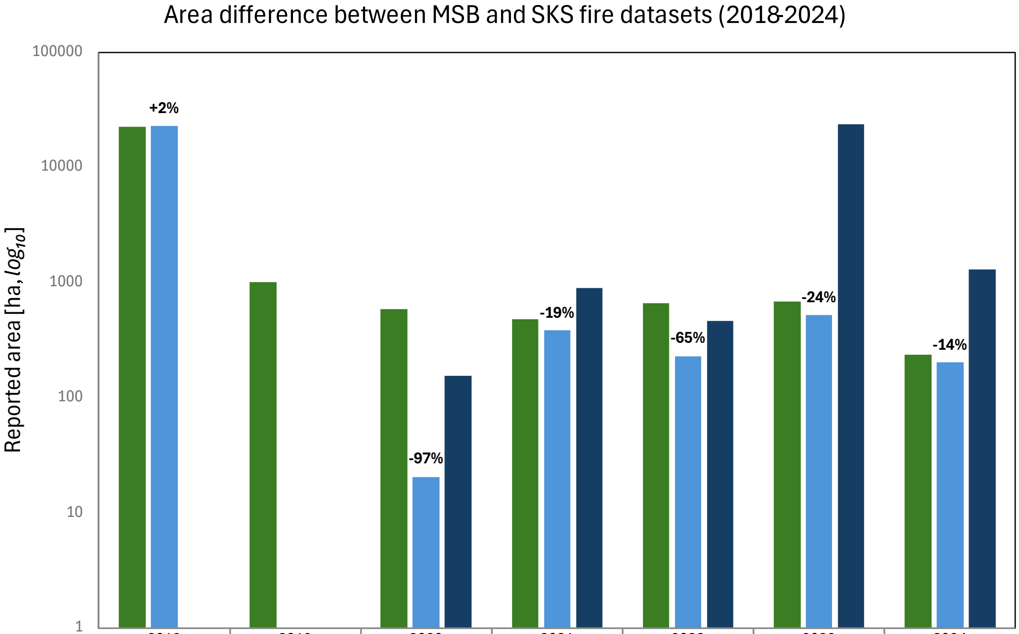


Figure 4. Relative difference in burnt area and number of fire events between MSB and SKS v.2 datasets for the years 2020–2024.

In contrast, SKS v.2 exhibited problematic discrepancies. As shown in Figure 4, SKS v.2 overestimated the fire area drastically in several years, most notably in 2023, where values exceeded MSB's reported area by over 3000%. Investigation in QGIS revealed that this spike was caused by missing or incorrectly entered event dates in the SKS v.2 attribute table. Additionally, v.2 lacked fire type classifications and specific fire dates, which are essential for emissions estimation. Based on this, SKS v.1 was selected for further analysis in this study.



	2018	2019	2020	2021	2022	2023	2024
MSB	22453	1006	592	478	656	687	236
SKS(v.1)	22866	0	21	385	229	520	203
SKS(v.2)	0	0	155	902	461	23772	1295

Figure 5. Difference in total burnt area (ha) between MSB and SKS (v.1 and v.2) datasets, visualised on a logarithmic (log_{10}) scale for the years 2018–2024. The plot shows differences in reported burnt area across years. For v.1, which was had the better fit, relative differences are given.

Figure 5 illustrates the absolute area and the difference between SKS and MSB datasets using a logarithmic scale, which emphasises the magnitude of discrepancy across years. Despite known issues, such as occasional double reporting (e.g., in 2024 a fire near Jokkmokk was found in both MSB and SKS with the same date and size), SKS v.1 was considered the more reliable polygon dataset for biomass extraction and GHG estimation.

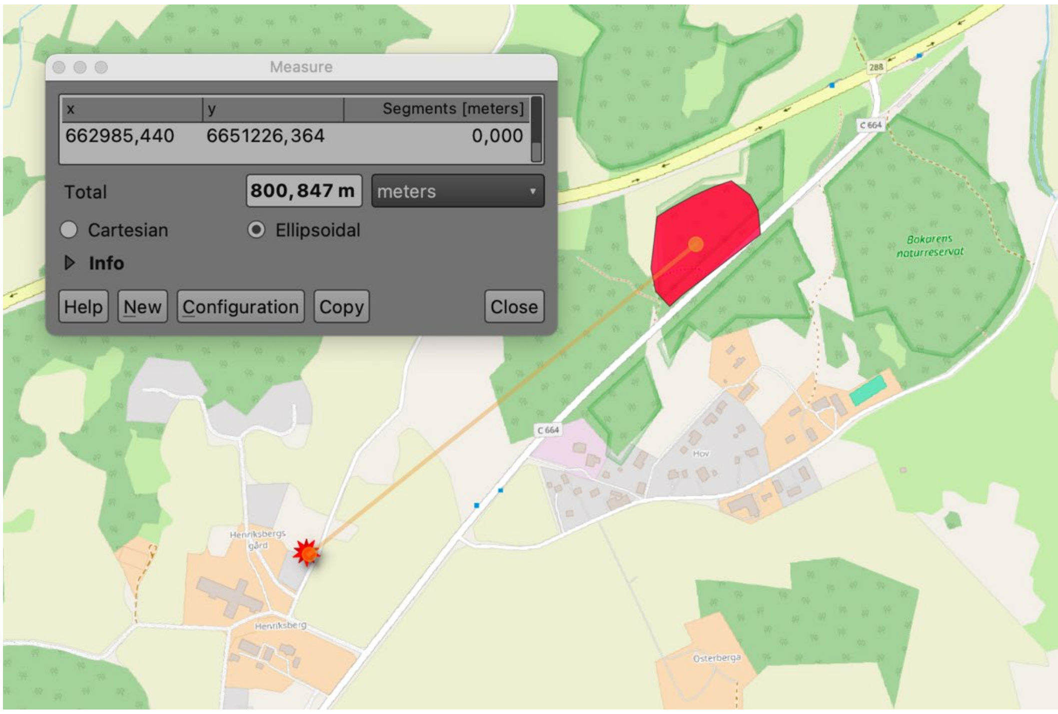


Figure 6. Field-based verification of SKS fire polygon accuracy. MSB data shows a minor fire (red star = point coordinate) listed with a 1 m² burn area. Nevertheless, the SKS dataset reported 2 ha of burnt area 800 m away on the same date. Field inspection revealed no evidence of fire. The discrepancy was likely caused by human misinterpretation of leaf-off deciduous forest.

A potential source of spatial overestimation was also identified during field validation. At one location in Uppsala county (fire 3, dated 11 October 2024, SKS-reported size: 2 ha), no burn signs were found (see Figure 6). MSB had recorded a 1 m² fire event, around 800m away, dated to 12 October. Discussions with SKS[8] suggested the polygon was based on remote image misinterpretation, possibly confusing leaf-off deciduous forest signs of recent fire. Even though this was likely a rather rare mistake, it highlights the need for estimating an error metric via field validation. A task that is not straightforward to do, as discussed later in section 4.1.

3.1.2 Controlled burnings: uncertainty in area reporting

Controlled burnings (i.e., regeneration and conservation burnings) constitute a significant share of Sweden's reported forest fire emissions. These fire types accounted for approximately 37% of the total burnt carbon from forest fires during the 2019–2023 period (Figure 7), while covering around 65% of the total burnt forest area (Ramberg et al., 2018).

[8] Personal correspondence with Frida Carlstedt

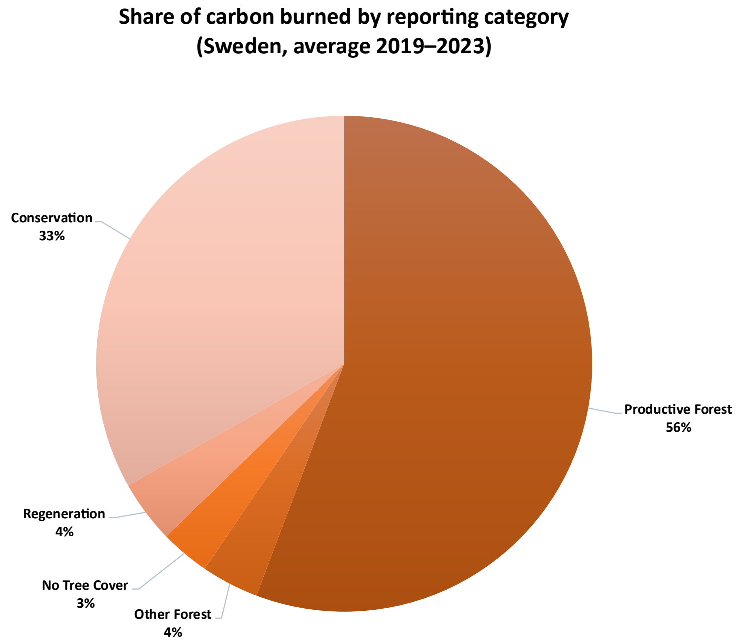


Figure 7. Average contribution of fire reporting categories to total carbon emissions from vegetation fires in Sweden, based on numbers from the current NIR for the period 2019–2023.

Controlled fire data are obtained via surveys of large forest owners conducted by SKS. However, validation against literature highlights possible inconsistencies in reporting. The comparison of findings from a study on controlled burnings in Sweden (Ramberg et al. 2018) with SKS reporting shows lower total burnt areas for regeneration fires in most years compared to SKS reports, with the exception of 2014 (Figure 8a). Conservation fires were reported as relatively similar but diverged in 2014 to an 110% difference, with SKS reporting more burnings (Figure 8b).

Figure 8. (a) Difference in area estimates for regeneration burning reported by SKS and Ramberg et al. (2018). (b) Difference in area estimates for conservation burning reported by SKS and Ramberg et al. (2018). Data represent reported burnt area (ha) per year for each burning type from 2011 to 2015.

3.2 Examination of combustion fraction assumptions

To assess how representative Sweden's current assumption of a 25% combustion fraction for living tree biomass is in field-context, six fire sites in central Sweden were visited during spring 2025. The selected locations represented a mix of wildfire and controlled burning events in productive and unproductive forest categories. At each site, indicators of burn severity were noted, including scorch height, damage to the moss and humus layers and occurance of tree mortality. The observations were based on expert judgment rather than standardized measurements, but can nevertheless provide valuable information about fire impacts under typical Swedish conditions. The following descriptions summarize the inspections at each site, offering an entry point for discussing the validity of the current assumption used in the national GHG emission reporting. Dates of the respective fire events are given as a temporal reference for the visual interpretation of the pictures.

Fire 1: Tensta (14.04.25)

Figure 9. Trees where only minorly affected by the fire.

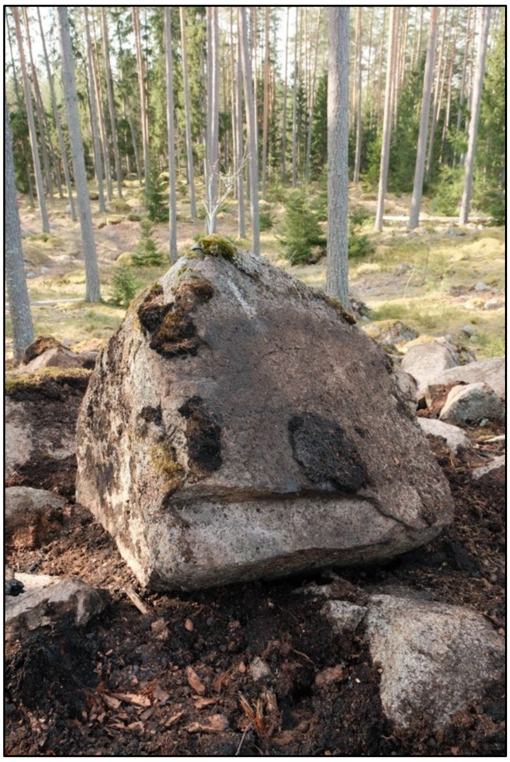


Figure 10. Moss on rocks was combusted almost completely.

This low-intensity wildfire burnt a roughly 500 m² patch of productive forest. Living tree damage was limited, with scorch height below 2 m and no obvious tree mortality (Figure 9). The moss layer (5–7 cm) and shallow humus layer (5–10 cm) were partially combusted, especially on exposed rocks (Figure 10). Ground-layer dwarf shrubs were affected only partly, and many small trees were still standing with unburned canopies. Estimated combustion of living biomass was well below 5%, possibly around 1%.

Fire 2: Gimo (04.04.25)

Figure 11. On the clear-cut area mostly small trees were affected, and regeneration had already begun.

Figure 12. In the older stand trees were affected up to 5 m.

This larger fire (6.4 ha) burnt through a clear-cut area with young spruce, as well as parts of an adjacent older stand. Burn intensity varied with local topography and moisture conditions. Ground vegetation was mostly burnt, especially dry grasses, though regeneration was already ongoing within the two weeks between the fire and the field visit (Figure 11). Tree scorch heights reached up to 5 m in some locations (Figure 12). Most small trees were heat-affected but mortality was hard to guess. Still, estimated combustion of standing living biomass remained low (<5%), though some deadwood and slash piles burnt more completely.

Fire 3: Bokarnes Nature Reserve (11.10.24)

At this location, no signs of fire were observed despite the presence of a mapped fire polygon. The forest appeared untouched. This suggests a false positive in the satellite-based fire polygon data, possibly caused by misinterpreted seasonal changes.

Fire 4: Norra Lunsen Nature Reserve (03.06.24)

Figure 13. Especially close to tree roots, the fire also burned into the ground.

Figure 14. Burning under the surface led to subsequent sinking of the ground in some places.

This fire (ca. 4 ha) showed the highest severity among the visited sites. It burnt into peat soils, causing root damage and uprooting several large trees. Scorch height on standing trees reached around 2 m. Some beetle-infested or already-dead trees had stronger combustion marks, but most live trees seemed only slightly affected. Peat smouldering reached depths of up to 20 cm in some places and caused holes around tree roots (Figure 13). In some parts the burning happened underground which led to subsequent sinking of the ground (Figure 14). Still, the combustion of living biomass was far below 25%, with most combustion affecting moss, peat, and deadwood not included in emission estimates from forest fires.

Fire 5: Hamra Nationalpark (21.05.24)

Figure 15. Scorch marks were seldom higher than 3 m.

Figure 16. Post-fire regeneration of dwarf shrubs on a burned stump.

This prescribed conservation burn covered about 6 ha and was low in intensity. Burn effects were patchy, with some moss layers combusted and others left intact. Tree scorch height reached 2-3 m (Figure 15), and no obvious tree mortality due to fire was observed. Most deadwood showed only minor surface charring, likely because fuel was removed before burning to reduce possible fire intensity. Post-fire regeneration of dwarf shrubs had already started (Figure 16). Overall combustion of living biomass was very low.

Fire 6: Hamra Nationalpark (04.06.23)

Figure 17. At some spots the shovel went in easily to 30 cm depth.

Figure 18. Measuring humus depth in the fire area as well as in adjacent areas was done for every fire. Regeneration of dwarf shrubs clearly took place.

This second conservation burn in Hamra (19 ha) occurred one year earlier. It showed similar characteristics to Fire 5, though moss combustion was deeper in some spots (up to the humus layer), especially in depressions that seemed humus-rich in adjacent stands (Figure 17). Regeneration was slightly more advanced than at Fire 5 (Figure 18), but fire intensity indicators were similar. No living trees appeared to have died from the fire yet, and most standing biomass was unaffected beyond 2-3 m. Again, fire severity was low and living biomass combustion minimal.

3.3 Biomass data analysis

3.3.1 Forst mask

An average above-ground carbon value of approximately 34 t C ha^{-1} was obtained for forested areas in Dalarna. When matched against SLU data for productive forest land in Dalarna, the NFI reported a mean of 36 t C ha^{-1} for the years 2019–2023. This was considered good enough for further use of the mask in biomass correction using forest growth (see 4.3 for discussion), which could then be used for estimation of fire available fuel at actual the fire sites.

3.3.2 Intersection of corrected biomass raster and fire polygons

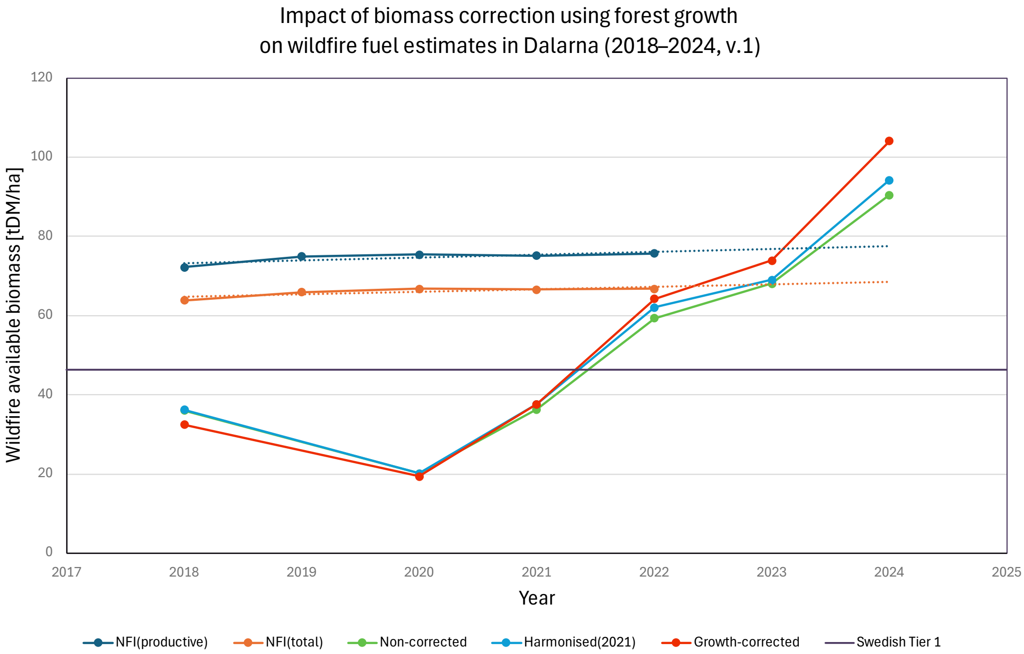


Figure 19. Impact of biomass correction using forest growth on estimated wildfire fuel loads in Dalarna (2018–2024) based on fire polygons from Dataset v.1. The chart compares three fire-area-specific biomass estimates – uncorrected values (green), values harmonised to a common reference year (2021) (light blue), and values growth-corrected to the year of fire occurrence (red) – against average forest biomass trends reported by the NFI for productive forest land (dark blue) and total forest land (orange). Current Swedish Tier 1 biomass assumption (purple) added as reference. The growth correction applied assumes an average annual increment of 3.5% for Dalarna.

Figure 19 illustrates the temporal dynamics of biomass availability in wildfire areas in Dalarna based on SKS v.1 fire polygons and how it compares to forest biomass trends reported by NFI. All three fire-specific lines (green, light blue, and red) represent variations of biomass estimates derived from the ALS-based biomass raster, while the two NFI reference lines (dark blue and orange) show reported averages for productive forest land (dark blue) and total forest land (orange). The green line reflects the average wildfire fuel loads (t dry matter ha^{-1}) extracted directly from the biomass raster without applying correction to it. Since the raster is a mosaic of ALS scans conducted in different years, each pixel value reflects the actual biomass at the time of scanning and not necessarily the biomass in the year the fire occurred. In this uncorrected approach, the average biomass per fire polygon over the seven-year period was 55.75 t dry matter ha^{-1}.

To harmonise biomass values across fire years, the ALS raster was normalised to a common reference year (2021) using the average annual biomass increment in Dalarna (see Appendix 1, Table 5). This produced the light blue line, showing a slight increase in the average biomass across fire areas to 57.26 t dry matter ha^{-1} (+2.71% compared to the uncorrected dataset). The final step applied a reverse growth correction to estimate the actual biomass present at the time of each fire (red). The average biomass across fire polygons using this correction rises to 58.98 t dry matter ha^{-1}, which is 3.00% higher than the harmonised version and 5.79% higher than the non-corrected version.

The graph also shows that while NFI-reported biomass averages remain stable or slightly increase over the observed period, fire polygon-specific biomass values show a notable rise from 2022 onwards. This likely reflects the fact that from 2022 on there were several nature conservation fires included, which potentially burnt in areas with higher biomass. To test this, nature conservation fires and regeneration fires were temporarily excluded from the dataset. The exclusion (not shown in the figure) resulted in a reduced mean biomass for 2022–2024, suggesting that nature conservation burnings indeed seem to be often carried out in more biomass-rich stands. Importantly, 2019 recorded no mapped SKS wildfires in Dalarna, while 2020–2021 show relatively low biomass values, reflecting the timing of ALS scans and fire occurrences in relation to forest development stages.

Due to the limited number of fires with clear classification as wildfires (only 13 out of 64 polygons), no stratification by fire type was applied here. The inclusion of unclassified burnings was necessary to maintain a sufficient sample size, though it introduces some interpretative uncertainty.

3.3.3 Biomass trends in NFI forest categories

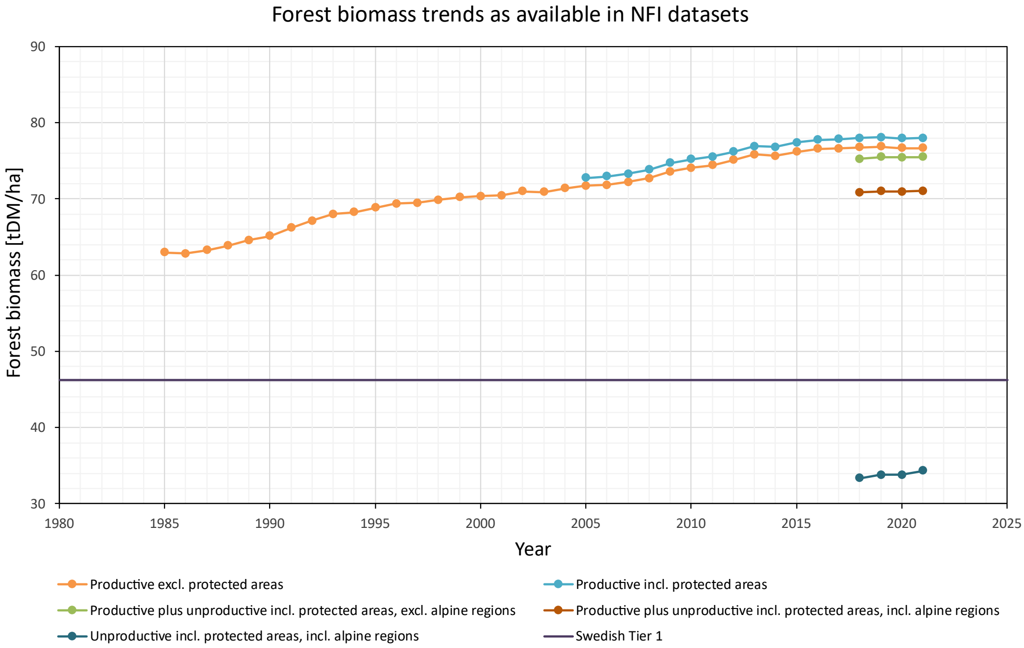


Figure 20. Trends in forest biomass stocks in Sweden (t dry matter ha^{-1}) between 1983 and 2021, based on NFI data. The graph shows aggregations of biomass averages by all forest categories that exist in Sweden: productive forest excluding protected areas (orange), productive forest including protected areas (light blue), and combinations including unproductive and alpine forest land (green and brown) as well as data for unproductive forest land (dark blue).

Figure 20 displays forest biomass trends (t dry matter ha^{-1}) over time across various forest categories, as compiled from NFI. The data series illustrate how forest biomass per hectare has developed from 1985 to 2021 for several national forest land definitions. The series for "productive forest excluding protected areas" extends back to 1985 and shows a continuous increase in average aboveground biomass from approximately 63 t dry matter ha^{-1} in 1985 to around 77 t dry matter ha^{-1} in 2021. A second data series, "Productive forest including protected areas", becomes available from 2005 onwards and reaches about 79 t dry matter ha^{-1} in 2021. This differentiation marks the first point at which protected areas were explicitly included in the NFI reporting. A further increase in land type differentiation appears in 2019, when alpine regions were added to the forest classification framework. The data on "productive plus unproductive including protected Areas but excluding Alpine Regions" shows values around 75–76 t dry matter ha^{-1}, while the category "Productive plus unproductive including protected areas and alpine regions" displays slightly lower values at approximately 70 t dry matter ha^{-1}. The "Unproductive including protected areas and alpine regions" category, only available from 2019, consistently shows the lowest biomass values, ranging between 34 and 36 t dry matter ha^{-1}.

Since the NFI does not report unproductive forest biomass separately, these values were calculated as the difference between total biomass in "Productive plus unproductive including protected areas and alpine regions" and "Productive including protected areas". Similarly, the total forest area for "Productive plus unproductive including protected areas but excluding alpine regions" was computed by summing the area of "Productive forest including protected areas" and "Unproductive forest excluding alpine regions." These biomass trends per hectare can be used as biomass values for fire in the different forest definitions available. For the following emission estimation methods, biomass from productive forest incl. protected areas is used, as this is the dominant forest biomass type in Sweden.

3.4 Comparison of emission estimation methods

Four calculation approaches were compared using data from the year 2021. This comparison focuses only on productive forest land. The methods include the IPCC Tier 1 (IPCC1) default approach, the Swedish Tier 1 method using a fixed national biomass assumption of 46 t dry matter ha^{-1} (Swe1), an updated version of the same method using recent national biomass data from the NFI (Swe2-N), and a regionally refined method based on county-level, area-weighted biomass averages (Swe2-CB). The difference in CH_4 and N_2O between IPCC1 and the Swedish methods is likely because the Swedish emission ratios are derived from values meant to be used for "open burning of cleared forests" as outlines in IPCC's 2003 Good Practice Guidelines (IPCC 2003). This approach might differ in it's effect on the gas ratio from the emission factors for "extra tropical forests" used in the IPCC1 method as suggested by the 2006 Guidelines for National Greenhouse Gas Inventories (IPCC 2006) for the use in boreal forests.

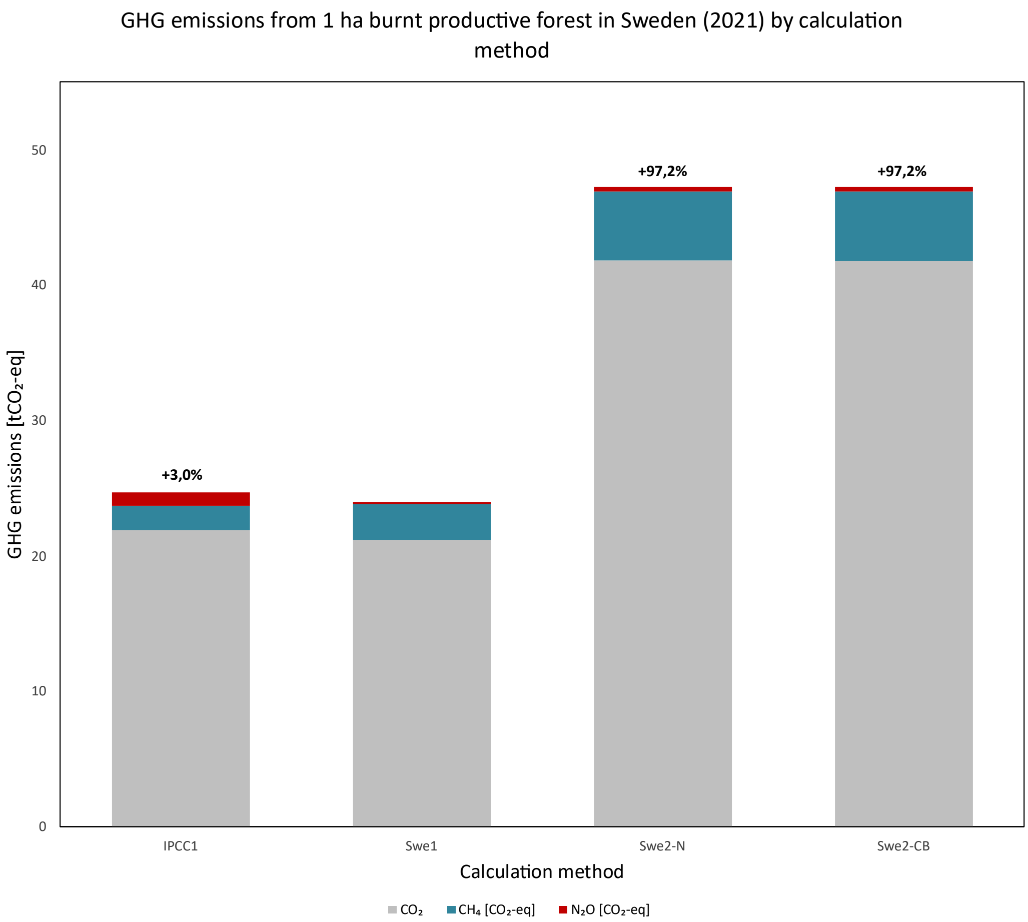


Figure 21. GHG emissions (in t CO_2-eq) per hectare of burnt productive forest in Sweden for the year 2021, calculated using four different methods: IPCC Tier 1 default, Swedish Tier 1 (Swe1), Swedish Tier 2 with updated NFI biomass data (Swe2-N), and Swedish Tier 2 with county-based weighted averages (Swe2-CB). Emissions are disaggregated by CO_2-equivalent of the considered gases (CO_2, CH_4, N_2O).

At the per-hectare level, emission estimates for a burnt area of productive forest have two distinct plateaus. While the IPCC1 and Swe1 methods arrive at relatively similar results (around 24 t CO_2-eq ha^{-1}), Swe2-N and Swe2-CB, with both being at 47 t CO_2-eq ha^{-1}, yield nearly double these values (Figure 21). Despite these differences in magnitude, the share of total GHG emissions from non-CO_2 gases (CH_4 and N_2O) remains low across all methods used, making up around 2–3% of total emissions.

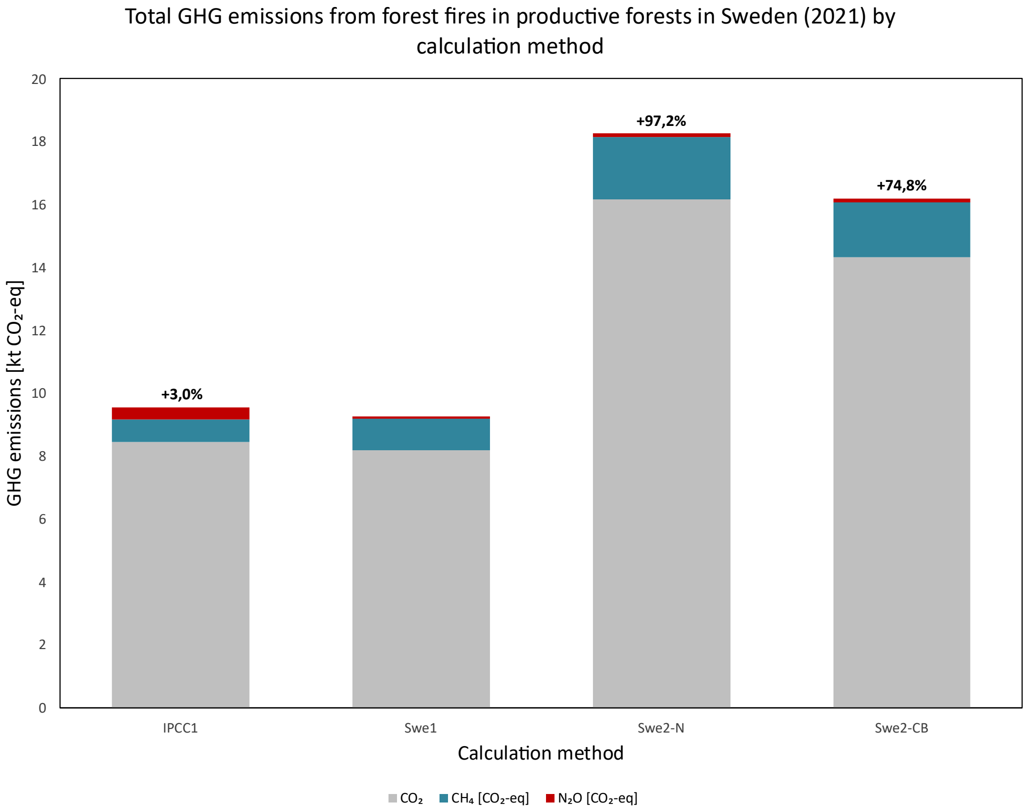


Figure 22. Total greenhouse gas emissions (in kt CO_2-eq) from forest fires in productive forests in Sweden for the year 2021, calculated using four different methods: IPCC Tier 1 default (IPCC1), Swedish Tier 1 (Swe1), Swedish Tier 2 with updated NFI biomass data (Swe2-N), and Swedish Tier 2 with county-based weighted averages (Swe2-CB). Emissions are disaggregated by CO_2-equivalent of the considered gases (CO_2, CH_4, N_2O).

When these per-hectare estimates are applied at the national scale, using the 2021 burnt area in productive forests, the difference between methods becomes more pronounced. Total GHG emissions for that year range from approximately 9 ktCO_2-eq under the IPCC1 and Swe1 approaches to 18 kt CO_2-eq using Swe2-N and 16 kt CO_2-eq with Swe2-CB (Figure 22). This is a difference of 75% to 100% between default and updated methods.

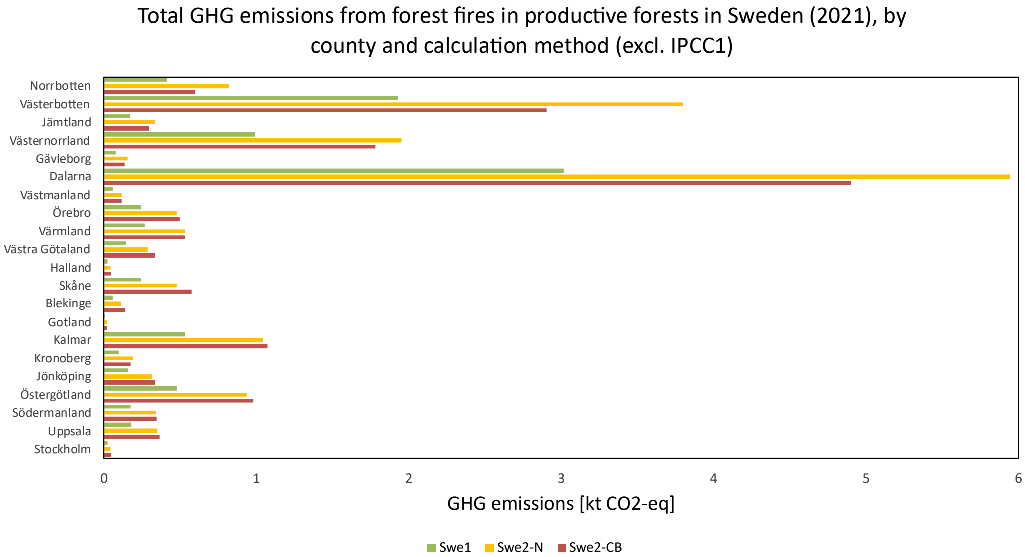


Figure 23. Total GHG emissions (in t CO_2-eq) from forest fires in productive forests across Swedish counties in 2021, shown by calculation methods: Swedish Tier 1 (Swe1), Swedish Tier 2 using new national biomass averages (Swe2-N), and Swedish Tier 2 with county-based weighted averages (Swe2-CB). IPCC1 is excluded, as its proportion to Swe1 stays the same and the values it produces are almost similar.

A spatial breakdown by county shows how these differences are distributed over counties (Figure 23). Emissions calculated with Swe2-N and Swe2-CB are consistently higher than previously reported across all regions, especially in counties with large burnt areas such as Dalarna, Västernorrland, and Västerbotten. The varying differences suggest that fixed national assumptions may under-represent emissions from forest fires in biomass-rich counties in the south of Sweden and over-represent them in biomass-poor counties in the north.

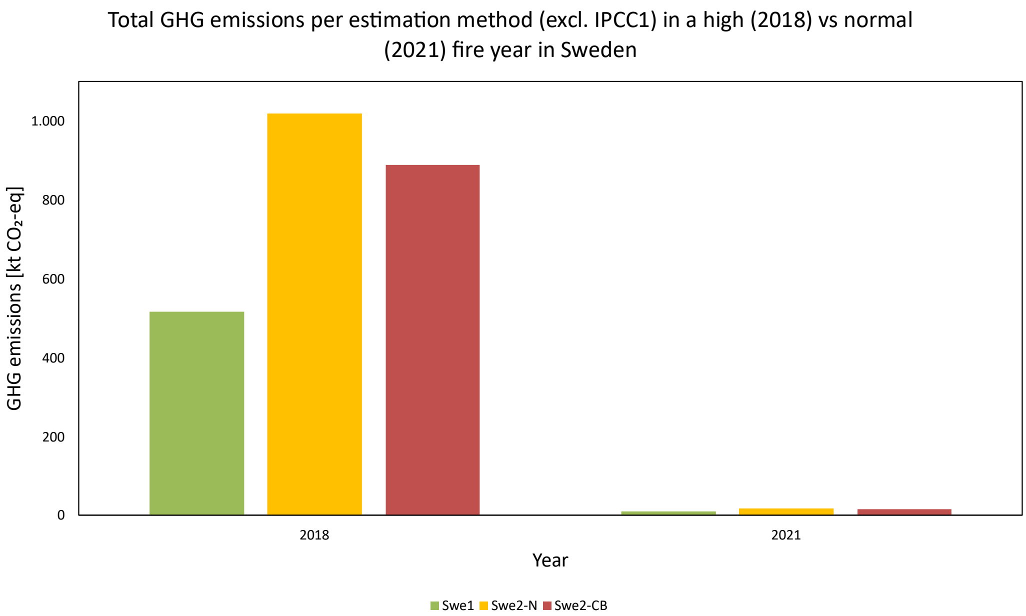


Figure 24. Comparison of total GHG emissions (in kt CO_2-eq) from forest fires in Sweden for a high fire year (2018) and a normal fire year (2021), using the approaches Swedish Tier 1 (Swe1), updated national biomass average (Swe2-N), and county-based weighted averages (Swe2-CB).

The effect of fire year variability is illustrated by comparing results for the high-fire year 2018 with the more moderate fire year 2021 (Figure 24). Total emissions in 2018 exceeded 1 Mt CO_2-eq when calculated with Swe2-N, while estimates using the IPCC1 method remained below 550 kt CO_2-eq. By contrast, the same methods yield only 17–18 kt CO_2-eq in 2021.

Method performance summary:

- The current Swedish Tier 1 method (Swe1) underestimates emissions due to outdated biomass values.
- IPCC Tier 1 (IPCC1) lacks specific national data, which Sweden has ample to offer.
- Swe2-N offers an improvement, keeping the biomass assumptions at the national level updated to the most recent value.
- The county-based method (Swe2-CB) offers the best spatial biomass resolution that is based on approved NFI estimates.

4. Discussion

This chapter discusses the outcomes of this study in the context of Sweden's existing framework for reporting GHG emissions from forest fires. Figure 25 provides an overview of the agencies and data involved in Sweden's current reporting system, as well as elements that could be added in the future to improve it. The aim is to clarify the information needs of the national inventory team and to point out where their work depends on data and coordination from and with other agencies within the existing institutional landscape.

It highlights two critical steps of the reporting: data acquisition and emission calculation method. An added colour scheme helps understand where the findings of this study see uncertainties in the respective agency data or method used. Guided by the results from database and field comparisons, biomass data analyses, and comparative assessments of different emission calculation methods, the discussion will take place around the core elements of GHG reporting: burnt area determination, combustion fraction/severity assumptions, biomass estimation, and finally the method used to calculate the emissions. Ultimately, the chapter concludes by synthesising these insights into recommendations for short-, medium-, and long-term methodological refinements, aimed at providing a rough roadmap for coming improvements of the Swedish GHG inventory.

4.1 Evaluation of reported burned areas

Accurate information on burnt area is a fundamental input for the reporting process. As illustrated in Figure 25, the initial step in reporting involves categorisation of fire events by responsible agencies (MSB for wildfires, SKS for wildfires over 0.5 ha and controlled burning), followed by estimation of burnt areas. This study's findings highlight several critical areas of uncertainty at this stage, affecting the reliability of Sweden's current forest fire emission estimates.

Regarding wildfire reporting, the comparison between SKS polygon datasets and MSB incident records revealed notable discrepancies arising from methodological differences. SKS area is primarily derived from remote sensing, which inherently limits their ability to detect smaller or lower-severity fires, which can in turn be captured by the municipal fire department's incident reports (MSB). The SKS dataset v.1 generally provided relatively reliable area estimates but systematically underestimated the number of fire occurrences compared to MSB data. This is mostly due to its inability to capture small fires. Nonetheless, increasingly smaller differences in recent years (2023 and 2024, Figure 3) might stem from improvements in SKS reporting methods and an increasing validation against other data sources.

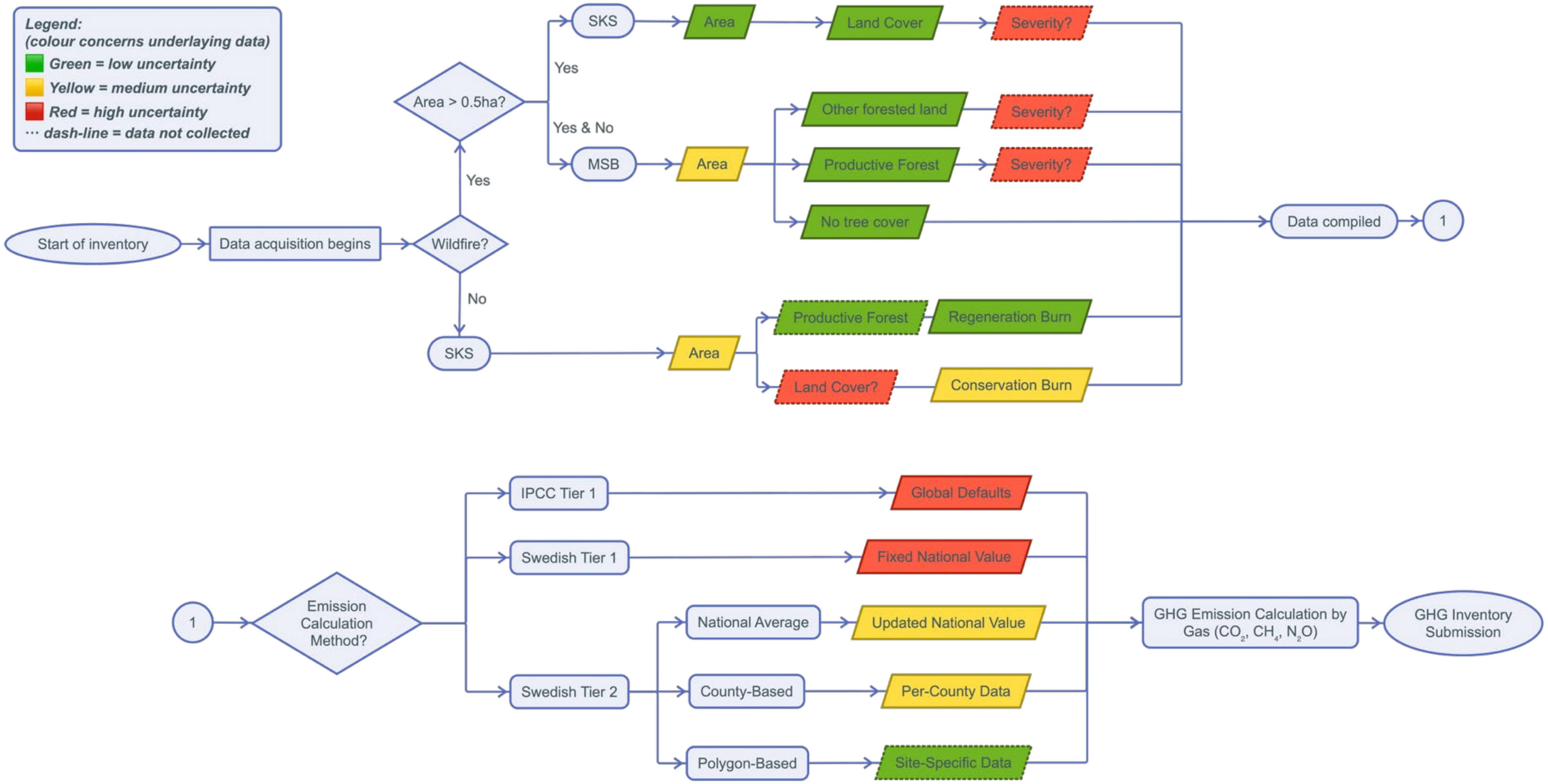


Figure 25. Overview of acquisition and classification pathways in Sweden's GHG inventory reporting scheme. The diagram highlights areas of low (green), medium (yellow), and high (red) uncertainty in underlying data from agencies. Dotted outlines indicate variables not collected. Wildfire data streams (SKS for more than 0.5 ha and MSB for all sizes) are distinguished from prescribed burnings (SKS)and it is shown, how they can be used in different GHG emission calculation methods (IPCC Tier 1, Swedish Tier 1, Swedish Tier 2 with sub-categories).

This trend in improvement shows the possibility that, with ongoing refinements, SKS polygons could soon become sufficiently accurate for use in spatially more granular emission inventories. However, some caution should remain, as shown with the SKS dataset v.2, that drastically overestimated burnt areas in certain years (notably 2023), due to incomplete metadata entries. While this issue will likely be solved soon and might not occur in that way ever again, it underscores the necessity for thorough validation checks on polygon data prior to emission calculations. This emphasises a noteworthy challenge faced in the preparation of the annual GHG inventory - relying on data from agencies whose primary mandates do not fully align with the specific requirements of GHG reporting. Data completeness and timeliness of information might thus be compromised at times.

Finally, as shown with the incorrectly mapped fire in Bokarnes Nature Reserve, some sources of uncertainty will persist. For spatially more explicit approaches, it might seem useful to assess the error in area difference between polygon delineation and ground truth. This might prove hard to do, as fires visited during the field trips often showed unclear boundaries or unburned areas within the fire area. Here further work needs to be done to come up with a workable solution.

In the reporting of controlled burning, uncertainty arises from unclear definitions and the way data is acquired. SKS collects data on conservation and regeneration burnings primarily through an annual survey of large-scale forestry companies, defined as companies managing more than 5000 hectares of forest land (Skogsstyrelsen 2022). This includes around 100 companies and covers approximately 11 million hectares, which is around 50% of Sweden's managed forest land. However, the survey excludes private individuals with holdings over 5000 hectares, formally protected areas, and all forest owners managing less than 5000 hectares, based on the assumption that regeneration and conservation burnings are conducted exclusively by large forest companies. While the survey, with its low non-response rate of about 2.5% and its annual frequency, can be considered reliable, some underreporting might persist, particularly conservation burnings in protected areas carried out by county boards (ibid., Naturvårdsverket 2023).

Contributing to the blurring of the categories of regeneration and conservation burn are the accreditation needs of FSC. According to the FSC standard, forest owners are required to burn 5% of the clear-cut area on dry-mesic land for conservation purposes. To reach this quota, so called "multipliers" can be applied to an area, reported as burned depending on the specifics of the forest in which the fire is conducted. For example, burnings on set-aside land receive a 3x higher weight than those on recently clear-cut areas. Retaining more than 30 % of the standing volume before burning multiplies the area burnt by 2 (FSC 2013). This incentive structure could nudge forest owners to classify fires as conservation burnings, even if conducted also for regeneration. This dual-purpose use of burnings has been documented in Sweden before (Granström 2001) and its occurrence complicates a clear classification of controlled burned areas into either the regeneration or conservation category. This also has implications for the underlaying fire severity assumptions as discussed under 4.2.

The misclassification problem is also reflected in the literature comparison. In 2014, SKS reported over 110% more conservation burn area than Ramberg et al. (2018), who collected data directly from FSC-certified companies and county administrative boards. This was also a year of high fire activity overall

(Naturvårdsverket, 2024). This could mean that SKS was classifying some wildfire areas wrongly as conservation or that forest owners underestimated their burnt area compared to the polygon delineated by SKS. The question of how SKS comes up with polygons for controlled burnings and how much of the total reported controlled burn this covers was not inspected in this work at all. Additionally, Ramberg et al. (2018) observed that 67% of prescribed burnings were conducted on clearcuts, reinforcing the possibility that many FSC-motivated burnings, while labelled as conservation burnings for standard accessibility, are regeneration burnings.

These findings suggest that, while the current reporting system provides valuable and broadly accurate information for GHG emissions estimation, uncertainties remain. This seems to be especially due to the unclear boundary between regeneration and conservation burnings. Better data could be achieved by targeted improvements in area reporting practices (e.g., better mapping by forest owners) as well as refined categorisation methods for controlled burnings in combination with solid validation wherever possible.

4.2 Combustion fraction and burn severity assumptions

The second major source of uncertainty in Sweden's GHG emission reporting system relates to assumptions about the combustion fraction, which directly determines the amount of biomass that is presumed to have burnt during a forest fire event. As Figure 25 shows the data availability on this data is worst over all data categories The current reporting approach therefore applies a fixed combustion fraction value of 25% over all forest categories and fire types (Naturvårdsverket 2025) without being able to explicitly account for actual burn severity.

Field observations during this study showed that actual combustion of living biomass was significantly lower than the assumed 25%. Across all visited fire sites, the estimated combustion fractions were typically below 5%, more often closer to 1%. Even in the most severe observed case at Norra Lunsen Nature Reserve, where peat burning and uprooting of some trees occurred (both cases are assumed to be inventoried by the soil carbon inventory and are not accounted for in the emissions from biomass burning), the proportion of living tree biomass combusted remained far below the assumed default. The findings align with studies, which suggest that wildfires in boreal regions rarely combust substantial proportions of standing living biomass, typically leaving most mature trees intact while primarily consuming ground-level fuels and deadwood (Bond-Lamberty et al. 2007; Keeley 2009). That could mean that Sweden's current assumption systematically overestimates emissions, especially in low-severity fires, where predominantly moss, humus layers, and dead organic matter are affected. While the current Swedish GHG inventory includes dead biomass in their calculation (assuming 0.3–0.6% of the biomass is deadwood), the emissions from ground-layer combustion (moss, litter, peat) are theoretically captured through soil carbon inventory changes (Naturvårdsverket 2025). How many trees died years after the fire event could not be assessed during this study. For the context of conservation burning in Swedish conditions, it was found to be typically lower than 12 % (Sjöström et al. 2024). Still, this would not add them to the direct emissions from forest fires, as trees that die that way are not combusted but eventually decompose. Practically, accurately monitoring these emissions through the soil carbon pool remains challenging, particularly considering their spatial and temporal variability compared to the sample plots of the inventory.

Without quantifiable severity data at the polygon level, emission reporting needs to rely on assumptions. As severity might not be even within polygons, quantification of severity remains a challenging task. Enhanced assessments using remote sensing indices, such as dNBR (differenced Normalized Burn Ratio), could help get more nuanced combustion factors, at least for bigger fires, in the future (Cocke et al. 2005). Recent studies indicate, however, that detecting low-intensity surface fires could remain difficult, as it depends not only on the amount of vegetation burnt but also on whether subtle changes in the multispectral imagery time series are detectable beneath a denser forest canopy (Tienaho et al. 2025). As the largest part of Sweden's forests is coniferous (Sjöström et al. 2024), and the majority of fires are ground or surface fires this points to an important area in need of further research.

For controlled burnings, particularly conservation burnings, discrepancies may be even more pronounced. Given that a large proportion of prescribed burnings are conducted on clearcut areas which are selected for safe burning conditions (Granström 2001), it seems plausible that available fuel loads, particularly deadwood, are reduced compared to the circumstances given in wildfires. This could result in significantly lower combustion rates than currently assumed in the default emission factors. If such vague classification occurs, the Swedish National Inventory Report's use of higher carbon release assumptions for conservation burning (currently 5.78 t C ha^{-1} compared to 1.15 t C ha^{-1} for regeneration; Naturvårdsverket 2024) could lead to a systematic overestimation of emissions in the controlled burnings section. The assumed magnitude between regeneration and conservation burnings thus is likely to be high, especially given the potential misclassification between conservation and regeneration burnings. Updating the assumed burnt carbon to recent values (see section Figure 20) and lowering the assumed difference in burnt carbon between regeneration burnings and conservation burnings should be considered.

4.3 Biomass data and correction using forest growth

The estimation of forest fire available biomass is represented in the schematic illustration of Figure 25 by the land cover (i.e., productive forest, other forested land, no tree cover and the element for missing land cover classification). As biomass directly influences total emissions by providing the basis for calculating the burn fraction, the basis of its estimation and possible corrections applied to it are of significant relevance for Sweden's GHG inventory. The current Swedish Tier 1 methodology employs a fixed, nationally averaged biomass value (46 t dry matter ha^{-1}), derived from older NFI statistics. As demonstrated in Figure 20 this value no longer accurately represents the Swedish forest conditions of today. Higher biomass values were observed in the NFI datasets, pointing to a biomass of approximately 91 t dry matter ha^{-1} in productive forests, incl. protected areas. Using outdated biomass averages systematically underestimates the actual available biomass for forest fires, particularly in areas of South Sweden with biomass-rich forests.

By updating the national average biomass with more recent NFI data (Method Swe2-N), emission estimates increased by approximately 97.2 % for productive forest land. A yearly update of these biomass values in Sweden's national reporting is thus advisable as a straightforward and easy-to-implement short-term improvement. The county-level area-weighted biomass averages (Method Swe2-CB) introduced additional spatial granularity into biomass estimates, which led to moderate variations in emission estimates compared to the updated national averages This is not surprising, considering Sweden's geographical extent and north-south orientation and the underlying spatial variability of growing conditions and biomass. However, while providing better resolution, the practicality of this approach depends on the capacity of the inventory team to compile and process such detailed data on a yearly basis.

Further exploration of biomass corrections at a polygon-specific scale using ALS-derived raster data was conducted in the case study region of Dalarna. To do this, this study first applied a forest mask to extract only forest biomass for subsequent correction. When tested against NFI data, it underreported slightly. The explanation for the 2 t dry matter ha^{-1} lower value obtained in this study might be threefold: (1) There is a presence of unproductive forest land in the used NMD mask, which reduces overall biomass averages due to poorer growing conditions in those areas. This is further supported by the difference in total forest area used in the two estimates (with the NMD-derived forest area being slightly larger). Additionally, the NMD map itself is modelled and therefore contains errors. (2) The biomass map from Skogliga Grunddata ignores forested areas with a tree height < 3 m, whereas the NFI samples trees, starting with the diameter class 0-9 cm. Thereby it also captures small trees, increasing the overall biomass present per hectare compared to the ALS biomass map. (3) There is a temporal mismatch between the sources - the average biomass per hectare obtained from the biomass map is a combined patch of scans performed in 5 different years, while the NFI data is the 5-year average of five annual inventories. Acknowledging these limitations, the results obtained from the biomass masking seemed reasonably good enough to perform the correction calculations for disturbances and growth.

The growth correction using disturbances was finally not implemented due to three main reasons: Firstly, there were technical complications with raster algebra (conflicts between zero and NoData values). Secondly, a closer inspection of the dataset documentation revealed that the forest operations data was not intended for quantitative use at fine scales, as it lacked validation of area and a proper classification of operation type. Thirdly, the fire area actually affected by the disturbance mask was rather small in the tests. Thus, while the logic and infrastructure for a disturbance-adjusted biomass map are in place, this approach is not yet ready for application. Still, the method outlined in this project may offer a conceptual and technical basis for future improvements when higher-quality disturbance datasets become available. This led to the implementation of only the correction using forest growth.

Applying biomass correction using forest growth raised the average available biomass by nearly 5.8%, compared to uncorrected values. Nevertheless, polygon-specific biomass data and correction depend very much on data quality (most notably delineation and categorisation) and lastly also on enough polygons to gain statistical relevance. In the long term, the most accurate biomass estimation method would integrate spatially explicit ALS data corrected for both forest growth and post-scan disturbances like harvests, wind damage and fires. The decision matrix (Table 3) built in this study could help with the geospatial operations needed. However, technical hurdles and insufficiently precise disturbance data remain for the time being barriers to an immediate implementation.

Table 3. Decision Matrix for disturbance mask creation, showing each possible case for a biomass pixel.

Case No.	Per Pixel Case	Pixel	Calculation
1	ALS < Forest operation < Fire	Forest operation pixels:	Set biomass to 0.
		Fire pixels:	Adjust biomass to 0.75 of ALS-derived value.
		Overlapping pixels:	Set biomass to 0, as both disturbances occurred after ALS data was scanned.
2	ALS < Fire < Forest operation	Fire pixels:	Adjust biomass to 0.75 of ALS-derived value.
		Forest operation pixels:	Set biomass to 0.
		Overlapping pixels:	Set biomass to 0, as both disturbances occurred after ALS data was scanned.
3	Fire < ALS < Forest operation	Fire pixels:	Use ALS-derived biomass value.
		Forest operation pixels:	Set biomass to 0.
		Overlapping pixels:	Set biomass to 0, as forest operations occurred after ALS data was scanned.
4	Forest operation < ALS < Fire	Forest operation pixels:	Use ALS-derived biomass value.
		Fire pixels:	Adjust biomass to 0.75 of ALS-derived value.
		Overlapping pixels:	Adjust biomass to 0.75 of ALS-derived value, as fire occurred after ALS data was scanned.
5	Forest operation < Fire < ALS	All pixels:	Use ALS-derived biomass value, as it already shows post-disturbance conditions.
6	Fire < Forest operation < ALS	All pixels:	Use ALS-derived biomass value, as it already shows post-disturbance conditions.

4.4 Evaluation of Emission Estimation Methods

The final step in estimating GHG emissions from forest fires involves the choice of emission calculation method, each with varying levels of complexity, data requirements, and assumptions (see Figure 25). This study assessed four methods in detail: the IPCC Tier 1 default approach, the current Swedish Tier 1 method, a revised national biomass-based method (Swe2-N), and a county-level area-weighted biomass approach (Swe2-CB). Each method builds on the same general equation for emissions (Emissions = Area × Biomass × Combustion Fraction × Emission Factor) but differs in the definition of the input variables.

The IPCC Tier 1 method assumes default input values for boreal regions, offering some comparability in the northern hemisphere but lacking regional accuracy. In this study, it resulted in the lowest emission estimates due to rather conservative assumptions on biomass. While simple and easy to implement, it under-represents Sweden's actual forest conditions and biomass accumulation, particularly in productive forest areas. The Swedish Tier 1 method improves on this by integrating national numbers yet still uses outdated biomass values as well as a fixed combustion fraction, making it insensitive to spatial and temporal variation. This limitation was highlighted by an analysis of NFI statistics, which suggested significantly higher biomass value. Lower combustion fractions for the fires visited in the field were observed. Due to the limited scope of this study, the number of fires visited (n=6) cannot be taken for a statistically relevant result. Still, as all fires visited were of rather little severity, the results of this field visit raise doubt about the general validity of a 25% combustion assumption.

The Swe2-N method adjusted the Swedish Tier 1 method by updating biomass values based on the most recent NFI data. This nearly doubled the emission estimates for productive forest areas compared to the Swedish Tier 1 method, showing how sensitive national emissions from forest fires are to underlying biomass assumptions. This method uses a national average biomass value from the NFI data, making it very easy to implement while improving accuracy significantly. The Swe2-CB method additionally introduced spatial differentiation by using county-level area-weighted biomass values. This led to only moderate variation compared to Swe2-N but allows better alignment with regional differences in forest structure and productivity. As for the high fire year 2018, most fires happened in the middle-north part of Sweden, where biomass might be rather overestimated by a national average. If the fire distribution in 2018 is seen as representative for Sweden, then the Swe2-CB method could help reduce overestimations in those counties. Therefore, it can be considered to improve accuracy in biomass assumptions with relatively low additional effort, making it a strong candidate for near-term implementation.

Finally, a fire-polygon-specific approach using ALS-derived biomass data was tested in Dalarna. This method offers the highest spatial resolution, making it the potentially most accurate tested method. Nevertheless, its implementation at the national level would require substantial institutional and technical resources, as it depends heavily on data availability, processing capacity, and the precision of temporal disturbance data. This makes it an unfavourable candidate for immediate realisation, if methods with a better cost-benefit ratio are yet unimplemented.

A concluding note should be given to the use of the GWP-values from IPCC's Fifth Assessment Report in all of the performed calculations – 28 for CH_4 and 265 for N_2O (Myhre et al. 2013). This was done for comparability with the current Swedish reporting in this study and as that is the current practice for the reporting to the UNFCCC and the EU. Nevertheless, in the future it should be considered to update these values to the most recent GWPs from the IPCC's Sixth Assessment Report – 27 for CH_4 and 273 for N_2O (Forster et al. 2023). Using updated values in the calculations performed would have resulted in slightly different gas ratios, but the effect on the results is considered negligible considering the focus of this study.

4.5 Practical Implications and Recommendations

The findings from this work suggest a range of possible improvements for Sweden's GHG inventory that can be implemented step by step or in parallel if needed. Timeframes proposed are based on ease of implementation, urgence and data/method availability:

Short-Term Improvements (within 1–2 years)

- Replace outdated biomass values with recent NFI-based estimates for productive forests. This step is low-cost, annually repeatable, and brings emission estimates quite close to county-based averages without having to compile county-based data.
- Update to Emission factors from the 2006 IPCC Guidelines.
- Adjust emission factors for regeneration and conservation burning using more realistic biomass baselines and combustion rates. Especially for conservation burning, relatively lower combustion assumptions should be considered.
- Open a dialogue with SKS to share what data and metadata are ideally needed from fire polygons and data on controlled burnings, working towards better usability for the GHG inventory in the future.
- Use NFI-based area-weighted biomass averages at the county level to better reflect regional differences. This approach offers a good balance between spatial resolution and ease of compilation.

Medium-Term Improvements (2–5 years)

- Test and improve the fire-polygon-specific biomass estimation method using ALS-derived raster data corrected for forest growth and, if feasible, for disturbances. While demanding, this approach potentially offers the most realistic emissions estimates.
- Develop and test fire severity proxies for larger fires using remote sensing indices (like dNBR). This would help to get more accurate combustion factor estimates.
- Harmonise fire type definitions between SKS and the GHG inventory under consideration of the FSC standards. Clear guidelines on categorising regeneration and conservation burnings would help reduce systematic bias.
- Encourage SKS to explore the feasibility of expanding survey coverage for prescribed burnings to large private owners (>5000 ha forest land) and county boards.

Long-Term Improvements (5+ years)

- Invest in developing a national severity mapping system using remote sensing and field validation to derive adaptive combustion factors. The focus should be on large forest fires (100+ ha), as they have the greater potential to develop into higher severity fires.
- Foster long-term collaboration between MSB, SKS, SEPA, and SLU to ensure timely data sharing, technical dialogue, knowledge transfer, and consistent improvement of GHG-relevant datasets.

4.6 Methodological Reflections and Limitations

The most important limitation of this study lies in the exclusion of all carbon pools other than living tree biomass. Although this focus aligns with current Swedish reporting practices - where changes in forest soils are measured via the SFSI - and the primary research focus on living biomass, it ignores potentially substantial contributions from deadwood, litter, humus, and peat. Preliminary analysis, using the NFI average carbon stock for these pools, suggests that including these pools in the calculations could increase total emission estimates up to sevenfold. Particularly problematic is the underreporting of peat combustion, as peat is considered a fossil carbon pool that does not regenerate on a human timescale (Naturvårdsverket 2024b). The test the fit of the SFSI to capture GHG emission from forest fires related to these pools, was not scope of this study. But given that only around 2.3 SFSI plots (Mayer forthcoming) would have overlapped with the 200 km^2 burned area in the high-fire year 2018, any such representation might be highly insufficient to reflect actual emissions.

Another very relevant assumption relates to the uniform combustion factor of 25%, applied across all fires and fuel types. This is still the same as Sweden's current default. However, field visits conducted during this study suggest that actual combustion rates for living biomass were often much lower, typically under 5%. While using a fixed value simplifies calculations, it does not reflect observed fire severity, especially in low-intensity ground and surface fires that is the dominant fire type in Sweden (Shorohova et al. 2011).

Further limitations stem from the datasets used. Despite Sweden's open policy of publicly available environmental data, gaps in spatial coverage and data quality introduced some uncertainty. At the time of writing, the most recent national biomass map was still under development, and therefore ALS coverage was incomplete in the mountainous areas. As a result, this study used an older biomass raster. Some datasets also posed processing challenges. For instance, the classified peat map was only available at a 2x2 metre resolution, resulting in file sizes that needed dedicated computing resources. Similarly, the open-access version of the SKS dataset (v.2) had missing metadata fields, including fire type and year, making this version unusable for emissions analysis.

The growth correction applied to adjust biomass values in Dalarna County was based on a simplified linear growth factor of 3.5% annually. A more precise method would involve using the Heureka system which is capable of modelling stand-level dynamics based on forest attributes and management scenarios (Wikström et al. 2011; Nilsson et al. 2017),. Although more complex, such an approach would yield more accurate biomass estimates.

For the testing of site-specific data, geographic limitations apply. While Dalarna offers a reasonable compromise between northern and southern forest types, its fire regimes, forest structure, and management practices may not be representative for all of Sweden. So, while direct transfer of results should be treated with caution, transferring the methodology to other regions for further research can be pointed out as important. Also results that span more years of data than available today will be valuable in the future.

Validation of results from the calculations was not possible in the field. While six fire sites were visited and inspected, no standardized field protocol was used. As GHG emissions from fires are difficult to measure directly, official statistics formed the backbone of the analysis. While this was reasonable given scope and timeframe of this work, it restricts the possibility to validate the findings produced with ground-truth.

Additionally, different data-collecting agencies and their categorisation produced inconsistencies in data. For example, discrepancies arose in the classification of conservation and regeneration burnings. Although efforts were made to clarify these issues through correspondence with MSB and SKS, these attempts were only partially successful.

Overall, while this study represents an important step toward improving GHG emission estimates from forest fires in Sweden, several areas remain where future work could build upon with refinement. Expanding the analysis to include other carbon pools, improving combustion fraction estimates, and extending geographic and temporal coverage are promising directions for further research.

5. Conclusion

This thesis examined Sweden's current approach for estimating greenhouse gas emissions from forest fires and identified several key areas of improvement, amongst others an outdated biomass assumption, fixed combustion fractions, and inconsistencies in fire area reporting. With field observations, spatial data analyses, and a comparison of emission calculation methods, it demonstrated that more accurate estimates are achievable by integrating newer data and rethinking existing assumptions. The study showed that updating biomass values with recent NFI data nearly doubled emission estimates and that the assumed 25% combustion factor likely overstates real combustion, especially in low-severity fires. Additionally, the study could highlight ambiguities in classification between controlled burning categories, particularly regarding regeneration and conservation burning, due to differing incentives for reporting and the blurry boundary between these terms. To improve national GHG reporting, the thesis recommends short-term updates to biomass inputs, medium-term adoption of regionally differentiated methods, and long-term development of systems capable of integrating severity data and disturbance histories. These steps have the potential to make Sweden's forest fire emission reporting significantly better, taking it to a state where it can serve as a model for higher-tier methodologies in Europe.

References

Bond-Lamberty, B., Peckham, S.D., Ahl, D.E. & Gower, S.T. (2007). Fire as the dominant driver of central Canadian boreal forest carbon balance. *Nature*, 450 (7166), 89–92. https://doi.org/10.1038/nature06272

Cocke, A.E., Fulé, P.Z. & Crouse, J.E. (2005). Comparison of burn severity assessments using Differenced Normalized Burn Ratio and ground data. *International Journal of Wildland Fire*, 14 (2), 189–198. https://doi.org/10.1071/WF04010

FAO (2020). *Global Forest Resources Assessment 2020: Terms and Definitions*. (Forest Resource Assessment, 188). Food and Agriculture Organization of the United Nations. https://openknowledge.fao.org/server/api/core/bitstreams/531a9e1b-596d-4b07-b9fd-3103fb4d0e72/content [2025-06-12]

Forster, P., Storelvmo, T., Armour, W., Collins, W., Dufresne, J.-L., Lunt, D.J., Mauritsen, T., Palmer, M.D., Watanabe, M., Wild, M. & Zhang, H. (2023). The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., & Zhou, B. (eds) *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp. 923-1054, doi:10.1017/9781009157896.009.

French, N.H.F., Goovaerts, P. & Kasischke, E.S. (2004). Uncertainty in estimating carbon emissions from boreal forest fires. *Journal of Geophysical Research: Atmospheres*, 109 (D14). https://doi.org/10.1029/2003JD003635

Fridman, J., Holm, S., Nilsson, M., Nilsson, P., Ringvall, A.H. & Ståhl, G. (2014). Adapting National Forest Inventories to changing requirements – the case of the Swedish National Forest Inventory at the turn of the 20th century. *Silva Fennica*, 48 (3). https://www.silvafennica.fi/article/1095/keyword/sampling [2025-05-08]

FSC (2013). *The contribution of FSC certification to biodiversity in Swedish forests*. (2). Forest Stewardship Council. https://www.se.fsc.org/sites/default/files/2022-02/The%20contribution%20of%20FSC%20certification%20to%20biodiversity%20in%20Swedish%20forests_0.pdf [2025-05-11]

Granström, A. (2001). Fire Management for Biodiversity in the European Boreal Forest. *Scandinavian Journal of Forest Research*, 16 (S3), 62–69. https://doi.org/10.1080/028275801300090627

Granström, A. (2023). *En samlad svensk databas för bränder i skog och mark: aktörer, informationskällor och möjlig framtida samverkan*. Institutionen för skogens ekologi och skötsel, Sveriges lantbruksuniversitet.

Hijmans, R.J. (2025). *terra: Spatial data analysis*. https://CRAN.R-project.org/package=terra

IPCC (2003). *Good practice guidance for land use, land-use change and forestry*. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Papatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., & Wagner, F. (eds) (Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Papatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., & Wagner, F., eds). The Intergovernmental Panel on Climate Change. (IPPC National Greenhouse Gas Inventories Programme)

IPCC (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use*. (Chapter 2: Generic

Methodologies Applicable to Multiple Land-Use Categories). Institute for Global Environmental Strategies. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_02_Ch2_Generic.pdf [2025-01-28]

IPCC (2019). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.V., Zhai, P., Slade, R., Connoers, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, M., Belkacemi, M., & Malley, J. (eds). (Shukla, P. R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D. V., Zhai, P., Slade, R., Connoers, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, M., Belkacemi, M., & Malley, J., eds). In press.

Keeley, J.E. (2009). Fire intensity, fire severity and burn severity: a brief review and suggested usage. *International Journal of Wildland Fire*,. https://doi.org/10.1071/WF07049

Marklund, L.G. (1988). *Biomassafunktioner för tall, gran och björk i Sverige: Biomass functions for pine, spruce and birch in Sweden*.

Mayer, M. (forthcoming). Swedish Forest Soils and the Soil Monitoring Law: Comparing selected soil properties in the SFSI and the LUCAS Soil Survey and assessing the requirements laid down by upcoming EU legislation. Master's thesis. Swedish University of Agricultural Sciences, Department of Soil and Environment

MSB (2024a). Email correspondence with Joakim Ekberg

MSB (2024b). Quality declaration: MSB's statistics on the rescue services' operations in 2024. https://www.msb.se/siteassets/dokument/amnesomraden/skydd-mot-olyckor-och-farliga-amnen/raddningstjanst/statistik-raddningstjanst/kvalitetsdeklaration-statistik-over-raddningstjanstens-insatser2024.pdf [2025-05-16]

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T. & Zhang, H. (2013). *Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., & Midgley, P.M. (eds) (Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., & Midgley, P. M., eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf [2025-05-19]

Naturvårdsverket (2020). National Land Cover Database (NMD). https://geodata.naturvardsverket.se/nedladdning/marktacke/nmd2018/NMD2018_ProductDescription_ENG.pdf [2025-02-13]

Naturvårdsverket (2024a). National Inventory Report Sweden 2024: Annexes. Naturvårdsverket. https://unfccc.int/sites/default/files/resource/NIR%20SE%20submission%202024%20Annex.pdf [2025-01-28]

Naturvårdsverket (2024b). National Inventory Report Sweden 2024: Greenhouse Gas Emission Inventories 1990-2022. Naturvårdsverket. https://unfccc.int/documents/627663 [2025-01-28]

Naturvårdsverket (2025). *National Inventory Document Sweden 2025*. (Greenhouse Gas Emission Inventories 1990-2023). Swedish Environmental Protection Agency.

Naturvårdsverket & Skogsstyrelsen (2023). *Natur- och kulturvårdande skötsel av skog: Nationell strategi för skötsel av formellt skyddade och frivilligt avsatta skogar till 2030*. Naturvårdsverket.

Nilsson, M., Ahlkrona, E., Jönsson, C. & Allard, A. (2020). Regionala jämförelser mellan Nationella Marktäckedata och fältdata från Riksskogstaxeringen och NILS. https://www.naturvardsverket.se/4ac337/contentassets/37e8b38528774982b5840554f02a1f81/regionala-jamforelser-nmd.pdf [2025-03-02]

Nilsson, M., Nordkvist, K., Jonzén, J., Lindgren, N., Axensten, P., Wallerman, J., Egberth, M., Larsson, S., Nilsson, L., Eriksson, J. & Olsson, H. (2017). A nationwide forest attribute map of Sweden predicted using airborne laser scanning data and field data from the National Forest Inventory. *Remote Sensing of Environment*, 194, 447–454. https://doi.org/10.1016/j.rse.2016.10.022

QGIS Development Team (2021). *QGIS geographic information system*. QGIS Association. http://qgis.org

R Core Team (2024). *R: a language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Ramberg, E. (2017). Bränder på skogsmark i Sverige - En kartläggning och analys av spontana och kontrollerade bränder 2011-2015. https://stud.epsilon.slu.se/10154/1/ramberg_e_170413.pdf#:~:text=%EF%82%B7%20Produktiv%20mark%20inkluderande%20hyggen%3A,skogsbevuxna%20partier%20i%20bebyggda%20omr%C3%A5den [2025-05-16]

Ramberg, E., Strengbom, J. & Granath, G. (2018). Coordination through databases can improve prescribed burning as a conservation tool to promote forest biodiversity. *Ambio*, 47 (3), 298–306. https://doi.org/10.1007/s13280-017-0987-6

Rogers, B.M., Soja, A.J., Goulden, M.L. & Randerson, J.T. (2015). Influence of tree species on continental differences in boreal fires and climate feedbacks. *Nature Geoscience*, 8 (3), 228–234. https://doi.org/10.1038/ngeo2352

San-Miguel-Ayanz, J., Durrant, T., Boca, R., Maianti, P., Liberta', G., Jacome Felix Oom, D., Branco, A., De Rigo, D., Suarez-Moreno, M., Ferrari, D., Roglia, E., Scionti, N., Broglia, M., Onida, M., Tristan, A. & Loffler, P. (2023). Forest Fires in Europe, Middle East and North Africa 2022., Luxembourg, 2023. Publications Office of the European Union. https://doi.org/10.2760/348120

Shorohova, E., Kneeshaw, D., Kuuluvainen, T. & Gauthier, S. (2011). Variability and dynamics of old-growth forests in the circumboreal zone: implications for conservation, restoration and management. *Silva Fennica*, 45 (5). https://doi.org/10.14214/sf.72

Sjöström, J. & Granström, A. (2020). Skogsbränder och gräsbränder i Sverige - Trender och mönster under senare decennier., 2020. Myndigheten för samhällsskydd och beredskap (MSB)

Sjöström, J., Plathner, F.V. & Granström, A. (2024). Hur stora är växthusgasutsläppen vid naturvårdsbränning. (RISE Report 2024:39). https://doi.org/978-91-89896-97-0

Skogsstyrelsen (2022). Kvalitetsdeklaration: Åtgärder i skogsbruket. https://www.scb.se/contentassets/5c4d574011484230a3bb9696ed16c55f/jo0301_kd_2021_20220825.pdf [2025-05-07]

Skogsstyrelsen (2024). Utförda avverkningar - produktbeskrivning. https://www.skogsstyrelsen.se/globalassets/sjalvservice/karttjanster/geodatatjanster/produktbeskrivningar/utforda-avverkningar---produktbeskrivning.pdf [2025-03-25]

Skogsstyrelsen (2025a). Brandomraden - produktbeskrivning. https://www.skogsstyrelsen.se/globalassets/sjalvservice/karttjanster/geodatatjanster/produktbeskrivningar/brandomraden--produktbeskrivning.pdf [2025-02-03]

Skogsstyrelsen (2025b). Email correspondence with Frida Carlstedt

Skogsstyrelsen (2025c). *Skogliga Grunddata - web information*. https://www.skogsstyrelsen.se/e-tjanster-och-kartor/karttjanster/skogliga-grunddata/ [2025-05-03]

SLU (2022). *The Swedish National Forest Inventory (Riksskogstaxeringen)*. https://www.slu.se/en/Collaborative-Centres-and-Projects/the-swedish-national-forest-inventory/about-the-nfi/ [2025-05-16]

SLU (n.d.). *Forest statistics database (Skogsstatistikdatabas)*. https://skogsstatistik.slu.se/pxweb/en/OffStat/ [2025-05-16]

Sveriges Riksdag (1979). *Swedish Forestry Act (1979:429)*. https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/skogsvardslag-1979429_sfs-1979-429/ [2025-05-16]

Tienaho, N., Wittke ,S., Yrttimaa ,T., Kivimäki ,A., Puttonen ,E., Saarinen ,N. & Vastaranta, M. (2025). Examining low-intensity surface fires in boreal forests using sentinel-2 time series and bitemporal terrestrial laser scanning. *Scandinavian Journal of Forest Research*, 40 (1), 29–40. https://doi.org/10.1080/02827581.2025.2457469

Wikström, P., Edenius, L., Elfving, B., Eriksson, L.O., Lämås, T., Senesson, J., Öhman, K., Wallerman, J., Waller, C. & Klintbäck, F. (2011). The Heureka Forest Decision Support System: An Overview. *Mathematical and Computational Forestry & Natural-Resource Sciences*, 3 (2), 87–94

Popular science summary

Climate change is affecting our entire planet. One of its consequences is an increase in weather conditions that favour forest fires. These fires in turn, release greenhouse gases - such as carbon dioxide, methane, and nitrous oxide - into the atmosphere, further influencing our climate in complex ways. That's why it's important to estimate how much these fires actually emit. Countries like Sweden report these emissions to the United Nations as part of their official climate obligations. But how can we know how much is released, if we can't measure it directly in the air?

Right now, Sweden uses a relatively simple method. It assumes that every hectare of forest contains the same amount of biomass (mainly trees and other plant material) and that a fixed share of it - 25 percent - is burned when a fire occurs. This approach is based on what the Intergovernmental Panel on Climate Change (IPCC) calls a "Tier 1" method, which is meant for countries that don't have more detailed data available. Sweden, however, has better data to offer, for example from the National Forest Inventory, satellite-based biomass maps, and detailed fire records from different authorities. I combined these data sources to test whether more accurate emission estimates could be made. I also visited a number of burned forest areas myself and looked at how much of the trees, moss, and soil organic matter was affected by the fire.

It turns out that the current method likely underestimates the amount of biomass present before the fire - but overestimates how much of it is burned. That means the overall greenhouse gas emissions could be under- or overestimated, depending on the location and fire type. Using updated estimations of tree biomass in the forest and fire-area-specific data, my calculations showed that the current method could be improved significantly. However, I also found that current methods focus almost entirely on tree biomass. This overlooks other important sources of emissions - especially humus and peat layers in the soil. In a country like Sweden, where many forest soils are rich in organic matter, these layers can contribute significantly to greenhouse gas emissions. While there is a procedure to cature those emissions in the so called Swedih Forest Soil Inventory (SFSI), it does not seem appropriate and might need to be changed.

I also compared Sweden's official fire records with other databases and found that while they generally match, some improvements in completeness and precision are possible. This is especially important for nature conservation burnings, often also used for forest regeneration purposes. This double use makes the two difficult to distinguish and attribute correctly in the current reporting system.

With my work, I could show that while Sweden is data-wise ready to move towards a more detailed reporting of forest fire emissions, it might require some changes in how data is collected, attributed and shared between authorities. Forest fires may make up only a small fraction of Sweden's total greenhouse gas emissions today, but in a warming world, it would be naive to think that this will remain the case. This is why the time to think about better ways to estimate emissions is now. With my work I contributed a tiny part to this big eneavor.

Appendix 1

Table 4. Annual burned area and GHG emissions from biomass burning in Sweden by fire type and land category 1990-2022. "IE" indicated that emissions are reported elsewhere in the inventory. Data source NIR (2024), Annex, Table A3:2.17.

	Fire category [ha yr^{-1}]					Annual emissions [kt yr^{-1}]		
	Wildfire			Controlled burning				
Year	Forest	Sparsely covered by trees	No tree cover	Regeneration	Biodiversity	CO_2	N_2O	CH_4
1992	567	647	924	201	0	IE (18)	0.00053	0.077
1993	567	647	924	334	0	IE (18)	0.00055	0.080
1994	567	647	924	152	0	IE (18)	0.00053	0.076
1995	567	647	924	177	0	IE (18)	0.00053	0.077
1996	567	647	924	455	0	IE (19)	0.00056	0.082
1997	3810	1092	1484	1720	0	IE (96)	0.00288	0.419
1998	77	123	219	570	0	IE (5)	0.00015	0.022
1999	793	292	229	2493	200	IE (32)	0.00097	0.141
2000	583	329	439	1538	400	IE (28)	0.00084	0.122
2001	412	286	555	2744	600	IE (33)	0.00099	0.144
2002	875	413	305	3802	800	IE (50)	0.00151	0.220
2003	1316	1016	1665	3073	1000	IE (66)	0.00198	0.288
2004	895	350	437	3894	1200	IE (58)	0.00174	0.254
2005	664	474	423	3288	1400	IE (54)	0.00163	0.238
2006	4645	534	524	4103	1410	IE (143)	0.00429	0.623
2007	522	311	255	1650	377	IE (26)	0.00079	0.114
2008	4280	713	433	3284	2012	IE (142)	0.00427	0.621
2009	730	282	392	1613	256	IE (29)	0.00086	0.125
2010	143	136	241	434	99	IE (8)	0.00023	0.033
2011	348	309	285	1572	433	IE (23)	0.00070	0.105
2012	108	85	288	940	433	IE (10)	0.00031	0.046
2013	476	315	715	1120	539	IE (27)	0.00081	0.118
2014	10498	2123	2043	2796	1804	IE (278)	0.00834	1.213
2015	256	95	243	770	326	IE (15)	0.00046	0.062
2016	712	262	325	874	441	IE (28)	0.00084	0.122
2017	441	168	812	667	327	IE (20)	0.00061	0.089
2018	21580	874	1885	560	361	IE (474)	0.01421	2.067
2019	790	215	251	452	395	IE (27)	0.00080	0.117
2020	396	188	229	572	158	IE (15)	0.00044	0.064
2021	486	114	265	583	380	IE (20)	0.00061	0.089
2022	419	236	256	583	380	IE (19)	0.00058	0.084

Table 5. Unpublished NFI data on annual biomass growth for Dalarna (above + below ground) in t dry matter ha^{-1} per year. Distributed by basal area and age over all stand types.

	Stand age [years]							
Basal Area [m²/ha]	0–20	21–40	41–60	61–80	81–100	101–120	121+	Total
0–	0.8	2.0	1.6	1.2	1.0	0.8	0.7	1.0
10–	4.0	4.1	2.9	2.4	1.7	1.6	1.2	2.9
15–	5.4	5.4	4.1	3.2	2.5	2.0	1.5	3.7
20–	7.5	6.8	5.1	4.2	2.9	2.4	1.9	4.5
25–	7.3	8.3	6.5	5.1	3.8	3.0	2.4	5.4
30–	7.9	10.0	8.8	7.2	5.6	4.5	3.8	6.6
Total	1.3	5.2	5.3	4.9	3.7	3.0	2.1	3.5

Table 6. Values and their corresponding class and definition for NMD Base Map (Naturvårdsverket 2020, Table 2.)

Value	Class	Definition
111	Pine forest not on wetland	Tree-covered areas outside of wetlands with a total crown cover of >10% where >70% of the crown cover consists of pine. Trees are higher than 5 meters.
112	Spruce forest not on wetland	Tree-covered areas outside of wetlands with a total crown cover of >10% where >70% of the crown cover consists of spruce. Trees are higher than 5 meters.
113	Mixed coniferous not on wetland	Tree-covered areas outside of wetlands with a total crown cover of >10% where >70% consists of pine or spruce, but none of these species are >70%. Trees are higher than 5 meters.
114	Mixed forest not on wetland	Tree-covered areas outside of wetlands with a total crown cover of >10% where neither coniferous nor deciduous crown cover reaches >70%. Trees are higher than 5 meters.
115	Deciduous forest not on wetland	Tree-covered areas outside of wetlands with a total crown cover of >10% where >70% of the crown cover consists of deciduous trees (primarily birch, alder and/or aspen). Trees are higher than 5 meters.
116	Deciduous hardwood forest not on wetland	Tree-covered areas outside of wetlands with a total crown cover of >10% where >70% of the crown cover consists of deciduous trees, of which >50% is broad-leaved deciduous forest (mainly oak, beech, ash, elm, linden, maple, cherry and hornbeam). Trees are higher than 5 meters.
117	Deciduous forest with deciduous hardwood forest not on wetland	Tree-covered areas outside of wetlands with a total crown cover of >10% where >70% of the crown cover consists of deciduous trees, of which 20 - 50% is broad-leaved deciduous forest (mainly oak, beech, ash, elm, linden, maple, cherry and hornbeam). Trees are higher than 5 meters.

118	Temporarily non-forest not on wetland	Open and re-growing clear-felled, storm-felled or burnt areas outside of wetlands. Trees are less than 5 meters.
121	Pine forest on wetland	Tree-covered areas on wetlands with a total crown cover of >10% where >70% of the crown cover consists of pine. Trees are higher than 5 meters.
122	Spruce forest on wetland	Tree-covered areas on wetlands with a total crown cover of >10% where >70% of the crown cover consists of spruce. Trees are higher than 5 meters.
123	Mixed coniferous on wetland	Tree-covered areas on wetlands with a total crown cover of >10% where >70% consists of pine or spruce, but none of these species are >70%. Trees are higher than 5 meters.
124	Mixed forest on wetland	Tree-covered areas on wetlands with a total crown cover of >10% where neither coniferous nor deciduous crown cover reaches >70%. Trees are higher than 5 meters.
125	Deciduous forest on wetland	Tree-covered areas on wetlands with a total crown cover of >10% where >70% of the crown cover consists of deciduous trees (primarily birch, alder and/or aspen). Trees are higher than 5 meters.
126	Deciduous hardwood forest on wetland	Tree-covered areas on wetlands with a total crown cover of >10% where >70% of the crown cover consists of deciduous trees, of which >50% is broad-leaved deciduous forest (mainly oak, beech, ash, elm, linden, maple, cherry and hornbeam). Trees are higher than 5 meters.
127	Deciduous forest with deciduous hardwood forest on wetland	Tree-covered areas on wetlands with a total crown cover of >10% where >70% of the crown cover consists of deciduous trees, of which 20 - 50% is broad-leaved deciduous forest (mainly oak, beech, ash, elm, linden, maple, cherry and hornbeam). Trees are higher than 5 meters.

128	Temporarily non-forest on wetland	Open and re-growing clear-felled, storm-felled or burnt areas on wetlands. Trees are less than 5 meters.
2	Open wetland	Open land where the water for a large part of the year is close by, in or just above the ground surface.
3	Arable land	Agricultural land used for plant cultivation or kept in such a condition that it can be used for plant cultivation. The land should be able to be used without any special preparatory action other than the use of conventional farming methods and agricultural machinery. The soil can be used for plant cultivation every year. Exceptions can be made for an individual year if special circumstances exist.
41	Non-vegetated other open land	Other open land that is not wetland, arable land or exploited vegetation-free surfaces and has less than 10% vegetation coverage during the current vegetation period. The ground can be covered by moss and lichen.
42	Vegetated other open land	Other open land that is not wetland, arable land or exploited vegetation-free surfaces and has more than 10% vegetation coverage during the current vegetation period.

Publishing and archiving

Approved students' theses at SLU can be published online. As a student you own the copyright to your work and in such cases, you need to approve the publication. In connection with your approval of publication, SLU will process your personal data (name) to make the work searchable on the internet. You can revoke your consent at any time by contacting the library.

Even if you choose not to publish the work or if you revoke your approval, the thesis will be archived digitally according to archive legislation.

You will find links to SLU's publication agreement and SLU's processing of personal data and your rights on this page:

- https://libanswers.slu.se/en/faq/228318

Every author has to make an agreement, remove or add rows of consent depending on the number of authors. Please remove this text when no longer needed.

☒ YES, I, Markus Riemer, have read and agree to the agreement for publication and the personal data processing that takes place in connection with this

☐ NO, I/we do not give my/our permission to publish the full text of this work. However, the work will be uploaded for archiving and the metadata and summary will be visible and searchable.